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THESIS

REAL OPTIONS IN DEFENSE R&D: A DECISION TREE ANALYSIS APPROACH FOR OPTIONS TO DEFER, ABANDON, AND EXPAND

by

Mehmet Celiktas

December 2016

Thesis Advisor: Amilcar A. Menichini
Second Reader: Steven P. Landry

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REAL OPTIONS IN DEFENSE R&D: A DECISION TREE ANALYSIS APPROACH FOR OPTIONS TO DEFER, ABANDON, AND EXPAND

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Submitted in partial fulfillment of the
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from the

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LIST OF ACRONYMS AND ABBREVIATIONS

ACTUV	Anti-Submarine Warfare Continuous Trail Unmanned Vessel
ALIAS	Aircrew Labor In-Cockpit Automation System
ARPANET	Advanced Research Projects Agency Network
ASD (R&E)	Assistant Secretary of Defense for Research and Engineering
ASW	anti-submarine warfare
COLREGs	International Regulations for Preventing Collisions at Sea
CommEx	Communications Under Extreme RF Spectrum Conditions
DARPA	Defense Advanced Research Projects Agency
DOD	U.S. Department of Defense
DTA	decision tree analysis
MAD	market asset disclaimer
NPV	net present value
OECD	Organization for Economic Co-operation and Development
PPBS	Planning, Programming, and Budgeting System
R&D	research and development
RADR	risk-adjusted discount rate
ROA	real options analysis
ROV	real options valuation

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I. INTRODUCTION

Nations invest in defense research and development (R&D) projects to enhance their military capabilities (Mowery, 2010). The motivation behind defense R&D may include national security, global military competition, or even potential economic profits (Hartley, 2011; Mowery, 2010). Regardless of the expected benefits, the success of defense R&D projects depends highly on the scientific and technological infrastructure and the human capital of the respective country. Nevertheless, one very important issue that affects the overall success of defense R&D investment is the selection of the R&D project with the best potential outcome. Considering the limited resources as well as increasing accountability, transparency, and efficiency concerns, picking the best R&D project becomes an extremely important step for defense managers.

Defense R&D is a risky undertaking as the outcome is uncertain; therefore, decision makers should incorporate flexibility into investment decisions. Current evaluation methods, however, ignore the value of flexibility that can be attained by real options—i.e., the options to defer, abandon, and expand. The integration of relevant real options into the project evaluation process improves the net worth of R&D projects and helps decision makers benefit from uncertainties. To understand the role real options play in defense R&D and designate the best valuation approach, this chapter examines the characteristics of defense R&D and sets the groundwork of the thesis. To this aim, the first part studies the characteristics of defense R&D and suggests a better alternative to the current evaluation methods. The second part explains the purpose of the study. The third part states the research questions. The fourth part defines the scope of the thesis. The final part sets the outline of the remainder of the thesis.

A. DEFENSE R&D

This part presents the defense R&D definition and a set of comparable data, and discusses the importance and challenges associated with defense R&D. Furthermore, a brief discussion on the problems accompanies current evaluation methods is provided, and the proposed solution is introduced.

1. Definition and Data

The *Frascati Manual*—which was drafted by the Organization for Economic Co-operation and Development (OECD) nations in 1963, and revised in 2002 and 2015—provides the internationally recognized definition of research and development[1] (R&D) (OECD, 2015). The aim of the manual is to provide countries with standard concepts and statistical practices to measure and compare R&D activities across nations (OECD, 2015). Since "the *Frascati Manual* is the de facto R&D reference document across countries" (OECD, 2015, p. 22), reviewing the meaning of R&D as defined in the manual is essential. Accordingly, R&D "comprise[s] creative and systematic work undertaken in order to increase the stock of knowledge—including knowledge of humankind, culture and society—and to devise new applications of available knowledge" (OECD, 2015, p. 44). The *Frascati Manual* groups R&D activity into three elements: "basic research, applied research, and experimental development" (OECD, 2015, p. 45). The manual further defines five "must-have" criteria for R&D activities:

- novel [focused on new discoveries],
- creative [built on innovative ideas and hypotheses],
- uncertain [final outcome is unclear],
- systematic [planned and budgeted],
- transferable and/or reproducible. (p. 45)

Accordingly, the objective of R&D—whether basic research, applied research, or experimental development—is to find tangible discoveries that add on current knowledge by utilizing creativity with a systematic approach in an uncertain environment.

The *Frascati Manual* defines the roles of government—both as funder and as performer of R&D activities—by providing standard concepts to measure the R&D activities in the government sector, including health, education, public administration, and defense. The manual lacks a definition of defense R&D; however, we can think of defense R&D as the R&D activities absorbed by the military. In this sense, defense R&D

[1] The *Frascati Manual* adopts the term "research and experimental development" rather than "research and development (R&D)"; however, it uses them interchangeably.

adopts the Frascati definition, and its five criteria, for the activities that contribute to the military output.

Although a standard manual is established for R&D concepts and statistics, the published defense R&D data have some important problems, which are discussed by Mowery (2010) and Hartley (2011) in detail. These problems include the exclusion of privately funded defense R&D, secrecy issues related to national security, long-range program durations, and the lack of reliable measurement for the final output of an R&D project. OECD (2016) also admits the difficulty of estimating defense R&D data that are consistent with the Frascati Manual. Despite these limitations, comparable defense R&D data can be gathered from the OECD.Stat (2016a, 2016b) database. Detailed defense R&D data for OECD countries for the years between 2010 and 2015 are in Appendix A. Additionally, the countries with the highest budget figures are presented in Table 1.

Table 1. Defense R&D Data for OECD Countries with Highest Budget Figures.
Source: OECD.Stat (2016a, 2016b).

	2014[a] Defense R&D Budget	
Country	**Total Budget[b]**	**Percentage[c]**
United States	64,985.7	51.25
Korea	2,739.1	13.48
United Kingdom	2,307.5	16.85
Japan	1,472.0	4.42
Germany	1,152.5	3.85
France	1,108.3	6.63
Turkey	609.2	13.63
Australia	280.2	6.17

[a] Latest year every country in the list was able to supply data.
[b] U.S.$ millions, 2010 constant prices and purchasing power parities (PPPs).
[c] Defense R&D Budgets as Percentage of Total Government R&D Budget.

The eight countries listed in Table 1, which account for 99 percent of all OECD countries, spend a significant amount of budgetary funds for defense R&D activities. The outlier among them is the United States, which accounts for 86 percent of the entire OECD defense R&D budget. The share of defense R&D budget in total government R&D budget for these eight countries tends to be high. Again, the United States has the highest figure, which is more than half of total U.S. government R&D budget. Korea, the United Kingdom, and Turkey allocate around 15 percent of total governmental R&D budget to defense activities. In consequence, countries spend considerable amounts of funds for defense R&D projects; therefore, it is imperative to plan and allocate them accordingly.

2. Importance and Challenges

Countries spend taxpayers' money in defense R&D activities in an effort to expand their military capabilities through technological and scientific innovations (Mowery, 2010). Defense R&D has several benefits for the respective country in preserving national security, deterring potential adversaries, leveraging the competitive position, and providing economic benefits. Primarily, developing critical defense capabilities and national weapon systems is extremely crucial for a country's national security (Jang & Lee, 2011). Countries improve their capacity to eliminate any threats from potential adversaries provided they maintain technological superiority and competitive military power through constant enhancement of its state-of-the-art military capabilities. Several historical examples illustrate how technological advances in defense have improved the national security and changed the course of conflicts. These examples include, but are not limited to, the atomic bomb, the jet engine, satellite technology, and the space probe (Hermann, 2008).

Defense R&D aims at expanding the boundaries of defense technology and capabilities to respond to future military requirements and cope with global competition. In this regard, defense R&D is part of a country's long-term strategy rather than a means of satisfying immediate needs. The way the previously mentioned technological breakthroughs developed demonstrates that advanced military capability not only ensures national security but also provides deterrence by fostering prestige and veneration. The country that possesses the latest military technology—the longest range, the highest precision, the most destructive, or the lowest margin of error—gains substantial power to shape world politics. Moreover, as Hartley (2011) points out, since these capabilities are transferrable, and expensive, they provide the country with extraordinary economic benefits when traded to other countries that demand these capabilities.

However, there are several challenges with defense R&D that make decision making and capital budgeting extremely difficult. These challenges—which are mainly attributable to the nature of the R&D project—include its uniqueness, long project life, uncertain outcomes, and risks and uncertainties regarding the research and development process. First, since an R&D project is one of a kind, opportunities for developing models and procedures for evaluation and improvement are limited (Ceylan & Ford, 2002). For instance, the U.S. Department of Defense (DOD) Assistant Secretary of Defense for Research and Engineering (ASD [R&E]) Strategic Guidance states that the DOD has around 10,000 unique R&D projects decomposed into 17 distinct portfolios ranging from biomedical to space (2014). This wide range and exclusive nature of defense R&D prevents decision makers from gathering historical data and creating empirical standards, thereby making forecasts and plans under uncertainty very demanding.

Second, due to long project durations, conditions observed before the start of the project may change (Ceylan & Ford, 2002; Keat, 2012). Parnell, Jackson, Burk, Lehmkuhl, and Engelbrecht (1999) highlighted that the timeframe for a defense R&D project from initial planning to deployment is 10–25 years. An example that illustrates this duration is the Eurofighter Typhoon project, which lasted 18 years (Hartley, 2011). This extraordinarily long project life implies that optimal decisions at the start of the R&D project may become obsolete during the following phases.

Third, evaluating the effectiveness of R&D projects and measuring the defense R&D output accurately and reliably are complicated tasks (Hartley, 2011; Keat, 2012). Expected returns on R&D projects can be characterized by the value they add to the strategic aims of the country, which are generally intangible. For instance, DOD defines three principles for engaging in R&D activities: eliminating threats to national security, providing affordable military capabilities, and technologically surprising adversaries (ASD [R&E], 2014). Therefore, an R&D project for the United States is valuable to the extent that it adds value to these principles, which are extremely difficult to measure. Furthermore, combinations among individual project components add to the project uncertainty, thereby making the measurement of the outcomes more challenging (Ceylan & Ford, 2002; Hartley, 2011). R&D projects, unlike simple procurement processes, are composed of separate elements, all of which are mutually dependent. In fact, defense R&D projects are becoming even more and more integrated in nature in order to synchronize operations in every domain—namely ground, sea, air, space, and cyber (*Third Offset*, 2016). Therefore, measuring the real worth of defense R&D projects and making decisions are becoming more difficult than ever.

Another aspect of defense R&D that makes measurement more challenging is its spill-over effect (Okur, 2013). Military R&D projects—whether by their process or their outcome—largely influence civilian innovation and may have a substantial effect on the overall well-being of humans (Mowery, 2010). A well-known example is the U.S. Defense Advanced Research Projects Agency's (DARPA) Advanced Research Projects Agency Network (ARPANET). Initially a communications network based on digital protocols, ARPANET became the foundation of the Internet, which has a dramatic effect on the lives of people ("Paving the Way," n.d.). Since it is generally beyond the foresight of decision makers, this spill-over effect is an issue in measuring project outcomes, thus adding to the challenges associated with defense R&D project evaluation.

Finally, the characteristics of defense R&D that focus on innovation for future needs and exploration of the unknown, bring extraordinary risks and uncertainties. The global competitive environment and the increasingly complicated nature of new military capabilities even increase these uncertainties (*Third Offset*, 2016). Moreover, the success of defense R&D projects is extremely dependent on the innovative capabilities of human capital, which is another type of risk affecting the R&D process. All these uncertainties and risks related to defense R&D have a direct effect on the success of the projects. These risks, however, are mostly project-specific, or private, risks—which are the risks that are specific to the R&D project or to the agency conducting the project (Smith & McCardle, 1998; Steffens & Douglas, 2007). These project-specific risks significantly influence the R&D outcome and the success of the project. One may argue that market, or public, risks also influence an R&D project. This argument may sound logical, but it is very limited since there is no market that affects the R&D project directly or indirectly.

Market risks, though, should not be confused with external factors that affect the course of the R&D project. External factors may change the project preferences, or in some instances, the success of the R&D activity. For instance, if a nuclear threat occurs, R&D efforts may shift to countering this threat by focusing on innovation on protective gears. Relatedly, sometimes the success of the R&D project may depend on the outcome of an adversary's R&D outcome that can be assessed in the future. These external uncertainties and risks, however, should still be regarded as project-specific risks, because they can be overcome with internal capabilities, such as capacity of the scientists, the technological background possessed by the agency, and many other private factors. In this regard, project-specific risks affect the course of the R&D tremendously, and they should be dealt with when evaluating the projects.

3. Evaluation Methods: Problems and Proposed Solution

Despite the current defense environment, and the characteristics and challenges associated with defense R&D, decision makers still use traditional methods to evaluate defense R&D projects (Ceylan & Ford, 2002; Glaros, 2003). For instance, DOD uses the Planning, Programming, and Budgeting System (PPBS), which was introduced in 1960s and has been used to construct defense budget in a program-oriented, long-term fashion (DOD, 2013). As Glaros (2003) points out, the PPBS, like other traditional methods, fails to evaluate the real value of the investment in an uncertain environment in that it does not incorporate the value of flexibility.

When choosing among otherwise equal R&D projects, the net present value (NPV) is observed to be the most commonly used traditional method (Brealey, Myers, & Allen, 2008; Trigeorgis, 1996). The NPV method discounts future expected benefits and calculates the present value of the project with a discount rate adjusted to account for the risk of the project (Newton, Paxson, & Widdicks, 2004). In this sense, the NPV assigns the decision maker a passive role in that it does not provide the managers with flexibility to modify their decisions based on unexpected developments later through the project (Trigeorgis, 1996). The NPV approach assumes that everything will go as planned and ignores potential future decisions regarding the project (Newton et al., 2004). As a result of this deficiency, defense R&D projects are often declined because of systematic undervaluation and negative NPV calculations (Angelis, 2000). One way to circumvent these challenges is to be flexible, which allows planners to adjust their initial decisions as the uncertainties evolve. To do so, decision makers should integrate real options—i.e., options to defer, abandon, and expand—into the defense R&D project evaluation.

As soon as new information becomes available and a better strategy emerges, decision makers think of exercising the real options to avoid potential losses and to benefit from favorable returns. This way of thinking, in which managers regard defense R&D projects as real options, is called "real options thinking." Scholars have widely recognized the value that real options thinking adds to investment decisions. However, they differ on the appropriate approach to integrate real options into R&D projects. One group favors the real options valuation (ROV) approach, which draws its analogy from financial option pricing models that use market data. Others advocate the use of the decision tree analysis (DTA) approach, claiming that since R&D projects are mainly exposed to private risks, the ROV cannot be used. Considering the characteristics and risks associated with defense R&D projects, the DTA approach suggests a better valuation method for real options in defense R&D projects.

In sum, maintaining a competitive defense R&D program is very important for national security, deterrence, competition, and potential economic benefits. However, due to the nature of R&D projects—namely their uniqueness, long life, uncertain outcomes, and risks and uncertainties—making proper investment decisions becomes problematic. Considering the increased threat and competition in the global defense environment, it is imperative for militaries to not only maintain superior scientists and researchers, but also to enhance their decision making procedures in determining the type, timing, and the process of R&D projects. Decision makers, therefore, should choose the R&D projects that maximize benefits and minimize costs. To this aim, they need to dispense with traditional methods and employ new approaches that provide the flexibility to exploit uncertainties. One way to account for flexibility is to use real options in defense R&D projects. This way, decision makers can shape their decisions to change the course of the project as uncertainties evolve. Scholars agree that this approach, known as real options thinking, improves the value of the projects; however, they differ on the proper valuation approach (i.e., the ROV or the DTA). Nevertheless, the project-specific risks associated with defense R&D projects suggest that the DTA is a sounder approach than the ROV. This thesis, therefore, employs the DTA approach along with simple case studies to present the significance of real options thinking and to value the real options—options to defer, abandon, and expand—in defense R&D projects.

B. PURPOSE

The primary purpose of this thesis is to present the benefits of using real options in defense R&D projects. Employing the DTA approach along with case studies to value three separate real options—i.e., options to defer, abandon, and expand—supports this purpose by depicting the application of these options to defense R&D. Ultimately, this thesis argues that 1) the DTA is preferred to the ROV approach in valuing defense R&D projects that include real options; 2) the real options thinking approach improves the net worth of the project and has a significant effect on decision making; and 3) the value of real options can be calculated using the DTA approach. Moreover, the thesis contributes to both scholarship and practice. First, the study closes a gap in the literature by applying the DTA approach to defense R&D real options. Second, the study provides practitioners, namely defense decision makers, easy-to-apply real option models and an understanding of the use of real options in defense R&D.

C. RESEARCH QUESTIONS

The primary research question of this thesis is "how can real options be used in defense R&D?"

Secondary research questions are the following:

- Is the DTA a better approach than the ROV to value defense R&D projects with real options?
- What are the benefits of real options thinking in defense R&D?
- How can the options to defer, abandon, and expand be incorporated into defense R&D projects?

- How do the options to defer, abandon, and expand add value to defense R&D projects
- How can the value of the options to defer, abandon, and expand in defense R&D projects be calculated?

D. SCOPE

The scope of the thesis is limited to “real options in defense R&D projects.” Nevertheless, the literature review is kept broader to encompass corporate R&D in an effort to demonstrate both the level of real options studies and the rationale of employing the DTA approach in the study. Besides, the thesis provides three separate cases to evaluate the use of options to defer, abandon, and expand in defense R&D projects. Although the study analyzes these three types of real options in three specific cases, the conclusions drawn from the analysis are applicable to a wide range of real options practices in defense R&D projects.

E. THESIS OUTLINE

Chapter II reviews the literature on financial and real options, and examines the debate on whether to apply the ROV or the DTA to evaluate real options in defense R&D projects. Furthermore, the chapter examines the limited number of real options research in defense and discusses the importance of this study in the literature.

Chapter III reviews the methodology—i.e., case studies and the DTA—used in this study to answer the research question. This chapter also answers why simple cases are chosen rather than complex ones, and responds to the criticism of the DTA approach.

Chapter IV provides three separate case studies in defense R&D. By analyzing these cases, I will evaluate defense R&D projects with and without the options to defer, abandon, and expand, and provide models that demonstrate the use and value of real options in defense R&D.

Finally, Chapter V presents a summary of the study, conclusions, and recommendations.

II. REVIEW OF RELATED LITERATURE

This chapter examines the literature of financial and real options, and real option applications in corporate and defense R&D projects. Examining the contemporary approaches to real options applications, the advantages and limitations of these approaches, and the importance of seeing capital budgeting decisions as real options will eventually help answer the research questions of this thesis. Additionally, this chapter provides the groundwork for the methodology, namely the decision tree analysis, employed in this study to evaluate the role of real options in defense R&D. To this aim, the first section reviews the financial options and financial options pricing models, the real options, and the similarity between financial and real options, which is called the real option valuation approach. The second section of this chapter examines the studies on the ROV applications in R&D projects and the drawbacks of these applications. The third section reviews the literature that discusses the DTA as a better surrogate for valuing and modeling real options in R&D projects. The fourth section of this chapter, besides exploring the dichotomy between the ROV and the DTA supporters, examines the studies that highlight the importance of "real options thinking" as a strategic managerial tool. The fifth section reviews the research on the real options applications in defense, and defense R&D in particular. Finally, the last section closes the chapter with a brief summary and conclusion.

A. FINANCIAL AND REAL OPTIONS

Academic proponents of the ROV not only support the inherent similarity between financial and real options—they both provide the right, but not the commitment, to invest—but also adapt the financial option models to evaluate real options in R&D projects. In this regard, financial options and their pricing models have been the foundation of the ROV approach. Therefore, it has merit to revisit the literature on the financial and real options and the real options analogy in order to comprehend the underlying assumptions of the ROV and to evaluate its applicability to defense R&D projects.

1. Financial Options

Although option pricing theory goes back to 1900 when a French mathematician found an option pricing formula (Merton, 1973), it was not until after the Nobel Prize-winning work of Black and Scholes (1973) that financial options pricing gained popularity among both practitioners and academics (Newton et al., 2004). Trigeorgis (1996) identifies an option as "the right, without an associated symmetric obligation, to buy (if a call) or sell (if a put) a specified asset (e.g., common stock) by paying a prespecified price (the exercise or strike price) on or before a specified date (the expiration or maturity date)" (p. 69). In this sense, the right to exercise an option creates flexibility for the option holder, and this flexibility determines the value of an option.

As Trigeorgis (1996) discussed, options differ from futures contracts, which are commitments to trade assets in the future based on agreed upon conditions whether the parties like them or not. He states that as opposed to the payoff of a futures contract, which is symmetric in that it may move up or down comparable to the underlying asset, the payoff of an option is one-directional. As a result of this asymmetric characteristic, the investor has to pay an additional price to acquire an option. Newton et al. (2004) explain that "as the holder of the option can take any upside gain but opt to not take any downside loss, no financially rational person would write an option without expecting to receive some premium for doing so" (p. 115). Accordingly, the price of this premium is called the option price and is subject to option pricing models.

The option price is higher when the underlying asset is more volatile (Brealey et al., 2008). The volatility, or the uncertainty associated with the future price of an asset, in essence, creates a risky situation for investors. As its volatility increases, asset price may skyrocket; and to the same degree it may plummet, thus having the investor suffer a significant amount of loss. However, the asymmetry of options provides the option holder with potential favorable benefits while protecting against any harmful consequences (Trigeorgis, 1996). Therefore, the option holder enjoys the ability to exploit the uncertainty in exchange for the option price.

Financial options are grouped into two categories: *call* and *put*. Brealey et al. (2008) explain the difference: "Whereas the call option gives you the right to buy a share for a specified exercise price, the comparable put gives you the right to sell the share" (p. 567). Further classifying of the options is based on the timing of their exercise: "If the option can be exercised only on one particular day, it is conventionally known as a *European call* [or *European put*]; in other cases … , the option can be exercised on or at any time before that day, and it is known as an *American call* [or *American put*]" (Brealey et al., 2008, p. 565). The flexibility to exercise any time before the maturity makes American options more valuable compared to European options (Trigeorgis, 1996). However, this flexibility makes an American option much more difficult to price (Newton et al., 2004). Accordingly, scholars apply European options to their financial and real options valuation models.

Academics and practitioners evaluate the value of financial options with a variety of models. These models are classified as continuous-time models (e.g., the Black-Scholes (1973) Model), discrete-time models (e.g., the Binomial Model of Cox, Ross, and Rubinstein (1979)), and other complex models (e.g., the compound model of Geske (1979)). Two of these models—the Black-Scholes Option Pricing Model and the Binomial Model—are worth reviewing, since they are very prominent and commonly applied to real options (Perlitz, Peske, & Schrank, 1999). In the following part, I present the underlying logic of these models and briefly mention the necessary inputs and assumptions to work the formulas. For further reference, details and formulas are presented in the appendices. Accordingly, the Black-Scholes Options Pricing Model formula is in Appendix B, and the Binomial Model formula and the construction and solution of binomial lattices are in Appendix C.

The basic idea behind these financial option models is building a portfolio—which consists of buying a particular number of underlying assets and borrowing a specific amount at the risk-free rate to finance these assets—that exactly replicates the future option returns (Trigeorgis, 1996). The net cost of this "replicating portfolio" constitutes the option value. The replicating portfolio idea brings three main valuation assumptions with it. First, no arbitrage profit opportunities exist, meaning that the investor cannot make a profit by buying an asset at one price and selling it simultaneously at a higher price (Amram & Kulatilaka, 1999; Trigeorgis, 1996). Second, the underlying asset can be replicated with an appropriate number of traded assets (Mun, 2002). This assumption does not pose a challenge in pricing options for common stocks, which are abundant in the market and highly liquid. However, for real options, and especially for defense R&D real options, building an exact replica poses real problems, which I discuss in the following part. Finally, the replicating portfolio idea does not account for an investor's risk attitudes (Brealey et al., 2008; Trigeorgis, 1996). The assumption that the investor's opinions toward risk do not affect the option value leads to an alternative way to price the option, which is called the risk-neutral valuation (Brealey et al., 2008). The models, therefore, apply indifferently to conditions regardless of whether investors themselves are risk-preferring or risk-averse.

The variables needed to work the models are mainly derived from the market. These variables include the value of the underlying asset (S), the exercise price of the option (X), time to expiration of the option (I), the risk-free interest rate (r), and standard deviation of the returns (or the volatility of the underlying asset) (σ) (Trigeorgis, 1996). In order to work the formulas, models rely on similar assumptions (Black & Scholes, 1973; Cox et al., 1979). Briefly, these models assume that there are no dividends and transaction costs for the underlying asset, the short-term interest rate and the underlying asset volatility are both known and constant, and returns from the underlying asset follow lognormal distribution.

Besides similar inputs and assumptions, the Black-Scholes and the Binomial models have another important characteristic. As the time intervals decrease and the number of steps increase, the Binomial Model transforms into a continuous-time model, giving the same result as the Black-Scholes Model (Mun, 2002; Trigeorgis, 1996). Although the Black-Scholes Model is quicker to apply and provides more accurate results, several academics have praised the Binomial Model due to its mathematical simplicity (Lander & Pinches, 1998; Mun, 2002), versatility and wider range of applicability (Brealey et al. 2008), ability to handle complex options (Amram & Kulatilaka, 1999), and similarity with decision trees (Brandão, Dyer, & Hahn, 2005;

Brealey et al., 2008). Owing to these advantages, scholars have applied the Binomial Model to R&D real options more widely than the Black-Scholes Model.

2. Real Options

In his renowned article, Myers (1977) used the term “real options” for the first time. Since then, the real options concept has gotten significant attention from both academics and practitioners (Borison, 2005), leading to several studies on the idea (Triantis, 2005). Brealey et al. (2008) define real options as “options to modify projects” (p. 283). For defense R&D projects, this modification includes deferring, abandoning, and expanding the project as the uncertainties evolve. Dixit & Pindyck (1995) stated that capital investments are about options, which are “the right but not the obligation to take some action in the future” (p. 105). In this regard, real options allow decision makers to incorporate managerial flexibility by providing them with choices under uncertain and risky conditions

As for the taxonomy, real options are generally named after the specific functions they play and the type of flexibility they provide in the investment decisions (Copeland & Antikarov, 2001). Therefore, there is no specific number of real option types that academics agree on. For instance, Trigeorgis (1996) groups common real options into six categories: option to defer, stage, alter the scale (up or down), abandon, switch, and grow. Benaroch (2001) provides an even more detailed taxonomy by defining 13 different types of real options in technology projects. Revisiting these definitions has no value to the study. However, it is practical to define the three types of real options—i.e., option to defer, abandon, and expand—since they are used in this study to answer the research questions.

a. Option to Defer

The option to defer, also known as the option to delay or option to wait, gives the decision maker the right to defer the investment decision to learn about future outcomes (Copeland, Koller, & Murrin, 2000; Trigeorgis, 1996). As opposed to the traditional NPV analysis—which assesses projects as now-or-never investment opportunities—the deferment option gives the decision maker a chance to delay his decision until necessary information is available (Ehrhardt & Brigham, 2011). Delaying the decision and waiting for the right time have value in avoiding unnecessary money outlay, since most of the investments in defense R&D projects are irreversible. Accordingly, the option to defer can be used in defense R&D projects whose success depends on uncontrollable variables that will be resolved in the future.

b. Option to Abandon

The option to abandon, also known as the option to sell or option to exit, provides the decision maker with a right to abandon if the project becomes unsuccessful (Copeland et al., 2000; Ehrhardt & Brigham, 2011). Managers may choose to exercise the abandonment option once the project turns out unprofitable with negative NPV. Abandonment includes the liquidation of the project and the sale of assets for salvage value. However, for defense R&D projects, since there is no secondhand market for the projects, this option is generally exercised for no significant value (Brealey et al., 2008). Moreover, the abandonment decision should be made by fully accounting for every possible consequence. Trigeorgis (1996) warns that when exercised irrationally, abandonment may lead to the loss of accumulated capabilities, which are extremely important for a country's defense R&D activities. The option to abandon can be used in sequential defense R&D projects, which are designed as successive phases that start after the successful completion of the preceding phase.

c. Option to Expand

The option to expand gives the decision maker a right to start with a limited operation scale and expand the project later when the outcomes turn out favorably (Copeland et al., 2000; Trigeorgis, 1996). A typical example includes a pilot, or prototype, project followed by full-scale application if the pilot project proves successful (Benaroch, 2001). In this sense, the option to expand creates future growth opportunities when the initial project becomes successful, and safeguards against extreme losses if the program turns out unfavorably. Accordingly, the option to expand may be exercised in the final phase of defense R&D projects, in which the decision maker chooses to implement the project on a limited scale to test potential outcomes, and based on these outcomes, broaden the application of the project.

3. The Real Options Analogy

Real options valuation (ROV)— also known as real options analysis (ROA)—in its narrower sense, is the application of financial options pricing models to non-financial assets, especially to investment opportunities (Amram & Kulatilaka, 1999). The rationale for this application is that real options, like financial options, give the owner a flexible alternative under uncertain conditions (Trigeorgis, 1996). Building on this logic, scholars advocating the ROV state that the models devised to price financial options can successfully be employed to value real options in investment decisions.

The analogy between real options and financial options has been extensively recognized among scholars, since both options provide the investor with the opportunity to take advantage of potential future earnings while controlling any loss (Angelis, 2000). At the heart of the ROV approach is the calculation of the value of an investment using market-based data (Borison, 2005; Steffens & Douglas 2007). The value, thus, represents "what the investment would trade for in the capital markets" (Borison, 2005, p. 18). This logic is also described by Amram and Kulatilaka (1999) as "[t]he options approach produces internal valuations of strategic business opportunities that are aligned with valuations in the financial markets" (p. 30). Therefore, the ROV approach builds on the same fundamentals as option pricing models, in that a replicating portfolio—or a tracking portfolio—of traded assets with similar returns as the underlying asset can be constructed and that the fair market value of the option with no arbitrage opportunity can be determined (Amram & Kulatilaka, 1999; Borison, 2005; Trigeorgis, 1996). To value the real options in investment decisions, the ROV attempts to institute similarities between the five variables in financial option pricing and those in investment opportunities. Table 2 summarizes the relationship of these five variables.

Table 2. Links between the Five Variables in Financial and Real Options. Adapted from Luehrman (1998).

Investment Opportunity	Variable	Financial Call Option
Value of the project	S	The value of the underlying asset
Investment amount to acquire the project assets	X	Exercise price
Time the decision may be deferred	T	Time to expiration of the option
Time value of money	r	Risk-free interest rate
Riskiness of the project	σ	Standard deviation of the returns

For more detailed explanation of this relationship, refer to Copeland and Antikarov (2001).

Scholars and practitioners have widely accepted this relationship. Several academics have conducted research using the ROV to model investment decisions and value the real options (e.g., Benninga & Tolkowsky, 2002; Borissiouk & Peli, 2001; Panayi & Trigeorgis, 1998; Perlitz et al., 1999). Moreover, there are also very comprehensive books on the theory and practice of real options (e.g., Amram & Kulatilaka, 1999; Copeland & Antikarov, 2001; Mun, 2002; Paxson, 2003; Trigeorgis, 1996). Although it is not practical to revisit every work on real options, I find it useful to review the ROV applications in R&D projects.

B. REAL OPTIONS VALUATION APPROACH TO R&D PROJECTS

Real options in R&D projects value uncertainty and flexibility, providing decision makers with options to manage decisions throughout the R&D project (Angelis, 2000; Paxson, 2001). To value these real options, several academics have proposed applying option pricing theory to R&D projects. They realized that the real options value in R&D investments should be captured when analyzing future investment opportunities (Angelis, 2000). Among these academics, Myers (1977), as mentioned earlier, is considered the first to build the analogy between financial market options and investment and growth opportunities outside the financial market. Myers (1977) suggested that the value of many corporate assets is attributable to call options in that this value of real options hinges on potential discretionary investments. Kester (1984), following Myers's (1977) analogy, claimed that capital investments are "analogous to ordinary call options in securities" (p. 154). According to Kester (1984), these investments create future growth opportunities for a company, where the real option value is affected by the uncertainty and deferability associated with the investment. Kester (1984) related R&D projects to compound growth options, and stated that these options "lead to new investment opportunities and affect the value of existing growth options" (p. 156). Myers (1984) further discussed the limitations of traditional approaches—i.e., the discounted cash flow analysis—in financial strategy and strategic planning, claiming that "[t]he value of R&D is almost all option value" (p. 135). In this sense, he advocated the superiority of the ROV approach over traditional techniques in strategic capital budgeting.

Mitchell and Hamilton (1988) defined the relationship between an R&D option and an American call option, suggesting a similar analogy to that in Table 2. They also pointed out that the unfavorable risk of a financial option—which is limited to the option price—is similar to the situation of an R&D option, in which the decision maker might choose not to invest in the following phase when things got worse, thus bearing only the initial investment cost with no additional commitment. Besides these similarities, they highlighted one very important advantage of the R&D option over financial options: "The purchase of a stock option has no direct effect on the exercise price or the future price of the stock, whereas the major purpose of the R&D option is to influence the future investment favorably, either by lowering costs or by increasing returns" (Mitchell & Hamilton, 1988, pp. 18–19). Hence, they highlighted one important strategic aspect of real options in R&D projects.

Ross (1991) suggested a call option analogy to value R&D investments by likening R&D units to "opportunity centers" in that "an opportunity center strives to maximize the upside potential of an R&D investment aimed at future opportunities" (p. 149). He further advocated that the ROV approach be used to value R&D projects, since the decision maker's choices affect the expected cash flows, which rules out the use of the NPV approach.

Numerous other authors have applied the ROV approach to R&D projects. Trigeorgis (1996) supported using ROV rather than traditional methods to value flexibility in R&D projects. Trigeorgis (1996) provided a comprehensive numerical example in which he used a binomial model that illustrated different competitive strategies for a firm’s R&D initiative. Panayi and Trigeorgis (1998) applied ROV to R&D projects by modeling growth options as compound, or multi-stage, options. They used two actual case studies—information infrastructure of a telecommunications authority and international expansion of a bank—to show that the ROV method can validate the projects, which otherwise would be rejected under the NPV rule (Panayi & Trigeorgis, 1998). Amram and Kulatilaka (1999) defined R&D as a platform investment that generates options, and stated that “[t]he real options approach values R&D by linking the R&D investment to opportunities it creates for follow-on investments” (p. 69). They provided a drug development application and suggested a model of sequential investments and abandonment options. Perlitz et al. (1999) highlighted the potential of applying ROV approaches to R&D projects by suggesting the compound model of Geske (1979) be used to value the R&D real options. Herath and Park (1999) emphasized the importance of using the ROV approach in R&D projects by building a binomial model for an R&D project. Borissiouk and Peli (2001) applied the ROV to an R&D case study at a biotechnology company. They built a multi-stage compound option model using the Binomial Model to assess the value of the R&D project. Benninga and Tolkowsky (2002) described the use of the real options—specifically an abandonment option—in R&D projects by applying the Binomial Model to a biotechnology R&D project. Hauschild and Reimsbach (2014) suggested a binomial model for sequential R&D investments. As is obvious, scholars have alternative approaches to apply the ROV approach to R&D projects. There is no blanket model for this application; every model in the academia uses distinct levels of complexity and different approaches. However, these applications have limitations.

Besides these authors, who advocate the beneficial application of ROV to R&D projects, several others have discussed the limitations of the ROV approach. An important criticism focuses on the complexity and therefore the inapplicability of the formulations. Faulkner (1996) claimed that although programming the Black-Scholes formula into a computer can facilitate the calculation of the option value, mathematical manipulations in the formula are not easily understood by managers, and therefore may create barriers to the acceptance of the formula variations. Moreover, Lander and Pinches

(1998) argued that decision makers do not know the ROV models well. They also stated that these models require high levels of mathematical skill; however, many managers, practitioners, and even academics lack this level of skills.

Other critiques of the ROV method highlight the inputs and assumptions of the models, which stem from option pricing models. The assumptions of the ROV approach basically hinge on the idea that since the risk associated with the investment corresponds to that of the market, the investment can be linked with a portfolio of market securities. According to some scholars, the market data to work the models are not necessarily present for R&D, therefore making the ROV models difficult to apply to R&D projects. Main critiques in this regard focus on the volatility and the lognormal distribution assumptions.

The assumption that R&D project volatility follows a predictable and constant pattern is profoundly criticized by many scholars. Newton et al. (2004) stated that the volatility of a financial option is derived from its historic data and readily available; however, the data for R&D projects, thus for the R&D real options, are very scarce, making the estimation extremely difficult. Similarly, Newton & Pearson (1994) examined the difficulties in gathering comparable R&D data needed to work the option pricing theories. Additionally, Paxson (2001; 2003) listed identifying the historical volatilities and finding suitable R&D data as a major problem in valuing R&D real options. Therefore, one of the main inputs of the ROV models for R&D real options is left unsupported.

In addition to the shortcomings in estimating the volatility, scholars have widely criticized the lognormal distribution assumption that is used to define the underlying asset value. Faulkner (1996) and Angelis (2000) argued that the assumption that future uncertainty can simply be described by a lognormal distribution is not suitable for the uncertainty of the outcomes of the R&D. Angelis (2000) stated that due to its underlying lognormal assumptions, the Black-Scholes Model is too difficult to be used in R&D project valuations. Angelis (2000) further claimed to provide a simplified model for R&D projects by relaxing some of the "unrealistic assumptions required by the Black-Scholes model" (p. 32). However, her model by itself could not overcome other limitations of the ROV approach.

Finally, but most importantly, scholars have criticized the no arbitrage/replicating portfolio assumption, which is the keystone of financial option models. Smith and McCardle (1998) stated that the essential principle of the ROV method is the replicating portfolio assumption, which dictates that “two investments with the same payoffs at all times and in all states—the project and the replicating portfolio—must have the same value” (p. 198). Newton et al. (2004) argued that the no arbitrage argument of the Black-Scholes Model and its variants requires the trade of the underlying asset. While this is valid for financial assets, it is (mostly) not applicable to R&D real options. Trigeorgis (1993) and Perlitz et al. (1999) stated that no market price could be found unless the underlying asset is traded; therefore, building a replicating portfolio to evaluate R&D real options is not possible. Borison (2005) claimed that there is little reason to accept the correlation between an individual investment and a replicating portfolio, stating that “[i]n the absence of arguments based on principle or evidence, the replicating portfolio assumption is difficult to accept” (p. 19). Pries, Åstebro, and Obeidi (2003) claimed that the requirement of finding a replicating portfolio—that reflects the same uncertainty as the R&D project as if it were traded—is hard to achieve. Smith and McCardle (1998) stated that the lack of serious applications of ROV to R&D projects is due to “the difficulty of finding replicating portfolios given the nature of the uncertainties associated with an R&D project” (p. 214). Accordingly, these scholars attack the very foundation of the option pricing models, claiming that the ROV approach to model and value R&D options is not realistic.

With an important study to circumvent the replicating portfolio problem, Copeland and Antikarov (2001), accepting the impracticality of finding a replicating portfolio and a market price for the investment, suggested an alternative method. They claimed that using the expected NPV of the underlying asset provides the most practical evaluation of the project value. They called this approach the “market asset disclaimer (MAD)” (pp. 94–95) and used it along with binomial models to show the broad range applicability of the approach, including the valuation of a pharmaceutical R&D project. Although Copeland and Antikarov (2001) bypassed the use of a replicating portfolio, the MAD approach is open to criticism in that it still relies on volatility estimation and lognormal distribution assumption. As stated by Borison (2005), considering subjective NPV assessment follows lognormal distribution is indeed impractical, which is an important limitation of the MAD approach.

In sum, the ROV approach has been widely used to model and value R&D projects. However, in practice, this approach poses significant problems that are rooted in the underlying assumptions of the models, which equate project risk with market risk. Although some scholars (e.g., Angelis, 2000; Copeland & Antikarov, 2001) have suggested alternative methods for circumventing these impractical assumptions, they cannot completely eradicate the limitations of the ROV applications in R&D projects.

C. DECISION TREE ANALYSIS APPROACH TO R&D PROJECTS

Several authors recognize the problems associated with ROV applications in R&D projects and have suggested that the DTA is a better modeling and valuation approach. Their rationale is that risks associated with R&D projects are inherent to the specific project and unique in nature; therefore, using a replicating portfolio, thus linking the market risk with that of the project, is misleading. Smith and McCardle (1998) stated that rather than the ROV approach, the DTA is commonly employed to evaluate R&D projects. They asserted that when there is no relevant market uncertainty, the R&D project should be regarded as a standard DTA. Similarly, Borison (2005) explained that because investment projects have unique characteristics—which lead to unique uncertainties—linking the project risk with that of the market, therefore using the ROV method, is misleading. Again, Dixit and Pindyck (1994) and Amram and Kulatilaka (2000) stated that the DTA be used for the projects whose values cannot be linked to market risks.

Recognizing the problems just discussed, several academics have used the DTA to model and value R&D projects. Morris, Teisberg, and Kolbe (1991) employed the DTA to illustrate potentially higher benefits of real options in riskier projects. They suggested that the R&D project with the highest risk is mostly preferred because the project with higher risk has higher expected cash flows if the project turns out to be successful. Morris et al. (1991) also explained how R&D projects with negative future cash flows can yield a positive value when the abandonment option is included in their sequential model.

Dixit and Pindyck (1995) illustrated the superiority of real options over traditional NPV analysis by applying the DTA approach to an R&D project of a hypothetical pharmaceutical company. In this case study, they demonstrated how an abandonment option increases the project value, and suggested that decisions—such as R&D investments—that create options have higher values than traditional NPV analysis. In this sense, projects that provide decision makers with more flexibility under uncertainty are more valuable than those projects that do not.

Faulkner (1996) used the DTA method to apply the abandonment option to a simplified R&D project, and demonstrated that embedding flexibility into R&D projects improve their values. He solved the R&D project decision tree and calculated the NPV of the project under different valuation methods, demonstrating that the DTA is a simple but effective approach for modeling and valuing real options. Faulkner (1996) also mentioned that he had performed sensitivity analyses that showed that the DTA can produce the same valuation as the Black-Scholes Model. Therefore, he suggested that the DTA is a better alternative for ROV in modeling and valuing R&D options.

Angelis (2002) questioned the applicability of the ROV approach—particularly the Black-Scholes Model—to R&D projects, claiming that the underlying assumptions of the model pose problems when applied to these projects. Angelis (2002), expanding on her earlier work (Angelis, 2000), presented a DTA-based model that can overcome the limitations of these assumptions and address both discrete and continuous distributions. Hence, she suggested that the DTA approach can overcome some inherent limitations of the ROV approach.

Steffens and Douglas (2007) used a defer option example from Copeland and Antikarov (2001) to explain the difference between the DTA and the ROV methods, illustrating the difficulties and problems with the ROV applications in R&D projects. They advocated that the DTA is more appropriate than the ROV for valuing technology investments, since all of the risks associated with this type of R&D project are firm-specific. As a result, they successfully exposed the limitations of the ROV approach and demonstrated that the DTA approach can practically be used to model and value real options in R&D projects.

Makropoulou (2011) refuted the advocates of the ROV—who claimed that the DTA leads to erroneous results—by portraying that under complete market conditions, the ROV and the DTA actually yield the same results. Additionally, he suggested that the ROV method cannot be used when the markets are not complete since the inputs to work the models require complete market data. Makropoulou (2011) also demonstrated that the misconception surrounding the DTA method is due to its naïve application of using similar discount rates for both the investment value and the expected cash flows of the project.

Some scholars have further argued that most investment projects in practice inevitably have both private and public risks. Therefore, they suggested integrating two approaches—the ROV and the DTA—to address both kinds of risks. Borison (2005) explained the basic assumption of these scholars as using market data for the public risk portion and counting on subjective analysis for the private risk portion.

Smith and Nau (1995) analyzed an investment decision with a deferral option, applying the ROV and the DTA approaches for both complete and incomplete markets. They concluded that, when applied correctly, the ROV and the DTA approaches give consistent values and strategies. Additionally, Smith and Nau (1995)—in addition to their conclusion that the ROV and the DTA results are compatible—demonstrated that the two approaches can be integrated when some risks of the projects can be hedged by the market.

Smith and McCardle (1998) exhibited the integration of the ROV and the DTA methods by developing and analyzing a model for valuing oil properties. They claimed that their integrated model could easily be applied to R&D projects and would give accurate results compared to the ROV approach. Moreover, they stressed that when the investment does not reflect any market uncertainty, their integrated approach in effect becomes a DTA approach. In this situation, subjective private information along with a risk-free discount rate would be used to value the investment and inherent real options.

Yao and Jaafari (2003) suggested applying the ROV along with the DTA to evaluate investment projects. They applied their integrated approach to a three-stage R&D project to model an abandonment option and calculate its value. According to Yao and Jaafari (2003), their approach provides greater advantage for valuing R&D real options by utilizing both the decision tree mapping and the ROV techniques.

All in all, several academics and practitioners have recognized the problems with the ROV application in R&D projects. Besides other limitations, the ROV method relates the market risk with that of the investment decision by creating a replicating portfolio. Since R&D projects are extensively associated with private risks, the ROV approach cannot properly deal with the evaluation of these projects. As a solution to the potential limitations of the ROV applications, scholars have suggested employing the DTA approach for R&D projects that contain solely private risks, and using an integrated approach—that combines the ROV with the DTA approach—for R&D projects that contain both private and market risks. Considering the private risks associated with defense R&D projects, the DTA approach provides a more promising valuation than the ROV; therefore, the DTA method is employed in this thesis.

D. REAL OPTIONS THINKING IN R&D PROJECTS

Although scholars argue on using different valuation approaches—i.e., the ROV and the DTA—they agree on one crucial point: the obsolescence of the NPV rule in valuing R&D projects. Scholars have discussed that managers should think of investment decisions as real options, in which risks and uncertainties can be addressed appropriately by incorporating managerial flexibility. This approach is called "real options thinking," which Steffens and Douglas (2007) define as "the managerial flexibility to capitalize on opportunities when they arise and/or to minimize the impact of threats" (p. 58). Steffens and Douglas (2007) also discussed the value of real options thinking as a strategic decision-making process in evaluating R&D projects, which are associated with high uncertainty and risk. Therefore, this approach helps decision makers benefit from risky investments and utilize uncertainties favorably as these uncertainties evolve. In this regard, many scholars and practitioners have highlighted the benefit of incorporating real options into R&D projects and the importance of real options thinking in managerial decision making.

Dixit and Pindyck (1995), by underscoring the inherent options in capital investments, stated that “thinking of investments as options substantially changes the theory and practice of decision making about capital investment” (p. 105). In this regard, they stressed the significance of establishing a better framework as a surrogate to the traditional NPV rule that would help managers deal with uncertainties, risks, and irreversibility more effectively. They further highlighted the importance of managers’ ability to incorporate options in investment decisions by stating that as the managers start to consider the real options in investment decisions, they become more experienced in evaluating uncertainties and controlling the flexibility.

Faulkner (1996) demonstrated the difference between traditional NPV thinking and real options thinking with a simplified DTA application. He stated that the real options thinking urges managers to approach adaptively to future uncertainties by anticipating the ability to monitor the outcomes of certain events and adjust the courses of actions accordingly. According to Faulkner (1996), real options thinking provides a richer view of uncertainty in that it shows decision makers that the opportunity for positive returns increases as the uncertainties in R&D projects increase. In this sense, real options thinking gives the decision maker a mindset that regards the uncertainty as a potential value to the investment and real options as a tool to take advantage of this value.

Amram and Kulatilaka (2000) define the real options approach as “a way of thinking that helps managers formulate their strategic options, the future opportunities that are created by today’s investments” (p. 15). In this regard, they see the real options thinking as a critical managerial tool that combines finance and strategy, and helps direct manager’s choices, valuation, and strategic decisions.

Triantis (2005) expressed that viewing investment and strategy decisions with a real options thinking framework will eventually make managers both more proactive in embedding flexibility in investment decisions and more reactive in responding to the uncertainties as they resolve. He suggested that "[r]ather than treating risk as something to be avoided, real options thinking encourages managers to view volatility as a potential source of value, with profound implications for the design of projects and corporate strategy" (p. 9). Accordingly, real options thinking as a strategic tool for decision making helps managers learn to make use of risky investments.

As a result, real options thinking has been widely accepted as a strategic aid in capital investment decision making. As scholars agree, viewing investments through the lens of real options prevents the systematic undervaluation of the projects and urges managers to see uncertainty as their ally. Therefore, facilitating real options design and implementation, thus benefiting from risks and uncertainties, is extremely important in planning and managing defense R&D projects.

E. REAL OPTIONS APPLICATIONS IN DEFENSE

As opposed to the numerous real options researches and applications in corporate settings, studies in defense are scarce; and for defense R&D even scarcer. There are, however, some outstanding articles that accentuate the importance of real options thinking and real options design and implementation in defense. These studies are not only on defense R&D, but also on defense acquisition and capital budgeting in general. Nevertheless, I find merit in reviewing some of these works, since it is important to visualize the level and progress of real options research in defense.

Ceylan and Ford (2002) applied real options to an R&D project selection example, illustrating that the use of scenario sets to design real options helps improve the value of projects. Their work supported the theory that real options thinking provides valuable insights to manage what they call "dynamic uncertainties" inherent in the acquisition of large complex defense projects. Ceylan and Ford (2002) also criticized the absence of an institutional practice of real options by stating that "[t]he lack of structured processes and tools for designing, valuing, and implementing options by practitioners, limits their assessment and improvement" (p. 253). They further suggested that real options thinking in large defense projects, as well as in R&D projects, increases the value of these projects and helps defense managers integrate flexibility into strategic decisions.

Glaros (2003) matched the DOD procurement inputs with those of the Black-Scholes Model by adapting Leslie and Michaels's (1997) approach. He suggested that the ROV techniques be employed to value real options in defense acquisition and R&D projects. Glaros (2003) claimed that applying real options to defense may "mitigate and minimize risk by opening up opportunities not achievable by DOD's rigid programmatic process" (p. 3). In this regard, he criticized the DOD's traditional tools, claiming that real options design in capital budgeting will overcome the shortfalls of the existing procedures. Glaros's (2003) work is also insightful for defense decision makers in that he discussed alternative uses of potential defense real options—i.e., options to invest, defer, divest, and options for acquisition and new product development.

Gregor (2003), by using a hypothetical case study, examined how real options can be integrated into the design and acquisition of naval ships. Gregor (2003) stated that the DTA is the best method for defense projects, because they lack historical data, replicating portfolio, lognormal distribution, and market risks. According to Gregor (2003), his findings suggested that public sector projects in general can utilize real options thinking and that the value derived by his method illustrates the scale and the importance of integrating flexibility into a project.

Olagbemiro (2008) and Olagbemiro, Mun, and Shing (2009) applied to DOD software acquisitions ROV—i.e., the Binomial Model—along with a risk management framework. They claimed that "the application of the real options valuation methodology would be beneficial as it would enable the DOD to incorporate the appropriate strategic options into the acquisition contracts" (p. 29). In this regard, Olagbemiro et al. (2009) advised the DOD to employ their proposed approach in order to enhance strategic defense investment decisions.

Jang and Lee's (2011) "eight-fold sequential compound option model" provides a very comprehensive work for the ROV applications to defense R&D projects. Jang and Lee (2011) applied their model to a case from the Republic of Korea, both to calculate the value of abandonment options and to illustrate the importance of defense decision makers adapting real options thinking for defense R&D projects.

Keat (2012) proposed a three-step evaluation methodology and a new theoretical framework for defense R&D investments in an effort to identify embedded real options in these projects and to designate appropriate ROV methods for evaluating them. Keat (2012), by demonstrating several exemplar case studies, provided an influential framework for strategic capital budgeting in defense R&D projects.

Angelis, Ford, and Dillard (2013) used the Javelin anti-tank missile system acquisition as a case study to value the abandonment option and to illustrate the importance of the real options thinking that allows decision makers to incorporate uncertainty. Angelis et al. (2013) described two uses of real options: 1) calculating flexibility in monetary terms that increase the value of projects and 2) real option design that can enhance project management and decision making practices. In this regard, she highlighted the importance of real options in defense as a strategic tool.

F. CHAPTER SUMMARY AND CONCLUSION

The ROV approach draws on the similarity between financial and real options, and uses models designed for financial options to value real options in investments. Although some scholars apply the ROV approach to R&D projects, others criticize the ROV and suggest that the DTA be used instead. The main critique rests on the idea that the ROV approach links market risk with the risk of R&D projects, assuming that these projects can be replicated in the market. Since most, if not all, of the risks related to R&D projects are project specific, the ROV approach leads to erroneous results. To overcome this limitation, scholars have advocated integrating the ROV and the DTA approaches to evaluate R&D projects that are exposed to both private and market risks, and using the DTA method to evaluate R&D projects that are influenced only by private risks. Due to the project-specific, or private, risks related to defense R&D projects, the DTA approach provides a more promising valuation than the ROV; therefore, it is the approach employed in this thesis.

Aside from the debate over the ROV and the DTA approaches, scholars agree that NPV as a capital budgeting tool is outdated in that it does not value managerial flexibility and does not account for uncertainties. Several scholars suggest that seeing investment decisions as real options helps decision makers manage uncertainty in a way that improves the value of the investment. This approach is called real options thinking and it is widely praised for its strategic value in capital budgeting.

Although numerous scholars and practitioners have conducted research to model and value real options in corporate R&D projects, real options research in defense R&D is very scarce; therefore, new studies are needed to expand the literature. This thesis is aimed at closing the gap in the literature by providing defense managers with decision making insights that successfully utilize the DTA to incorporate real options thinking into defense R&D projects. The thesis, therefore, should enhance defense managers' way of controlling uncertainty and valuing flexibility in defense R&D projects. To reach this aim, the study employs the methodology discussed in the following chapter.

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III. METHODOLOGY

As discussed in the previous chapter, the DTA approach is better than the ROV method in modeling and valuing defense R&D real options. To present how to apply real options using the DTA approach, this thesis relies on simple models, which are built on real defense R&D cases. The aim in using simplified cases is to provide practitioners with 1) practical and easy-to-employ models rather than accurate but poorly executed theories (Triantis, 2005) and 2) a clear illustration of how real options add value to defense R&D projects. In this sense, the thesis combines the DTA approach with the case study method and produces simple real option models. The use of this mixed methodology ultimately contributes to answering the research questions in two ways. The first is by illustrating how real options thinking in defense R&D projects enhances managers' decision making and adds strategic value to these projects. Second, this thesis shows how the DTA approach can be used to value real options in defense R&D projects. As suggested by several academics (e.g., Angelis et al., 2013; Bearley et al., 2008), the real options value in the DTA approach is calculated as the net present value (NPV) of the decision tree with the option less the NPV without the option. Accordingly, this chapter provides a detailed picture of the methodology used in the thesis to analyze and evaluate the real options in defense R&D projects. To this end, the first section describes the case study method and the advantages of using simple models over more complex ones. The second section explains the NPV analysis and its limitations in capital budgeting. The third section describes how the decision trees are built, and reviews and responds to some criticism of the DTA approach. Finally, the last section closes the chapter with a brief summary and conclusion.

A. CASE STUDY METHOD

A case study method is a study of a single unit of analysis (Eisenhardt, 1989; Polonsky & Waller, 2015). The primary goal of this method is to achieve an in-depth understanding of specific concepts and variables that in turn help formulate larger studies (Polonsky & Waller, 2015; Woodside & Wilson, 2003). This characteristic of the case study makes it a particularly important method for evaluating the role of real options in defense R&D projects. The defense R&D cases presented provide practitioners with practical applications and important insights into the use of real options (Kemna, 1993). To reach these objectives, this study uses a mixed methodology that incorporates the DTA with the case study method to create simple real option models, which are applicable to defense R&D projects in general.

1. Case Selection

For this study, ongoing DARPA projects are selected as cases. There are three reasons for using contemporary DARPA cases. First, as presented in the first chapter, the United States is by far the leading defense R&D investor (OECD.Stat, 2016b). Therefore, analyzing cases from the United States provides exemplar techniques not only for the United States, but also for the rest of the world. Second, DARPA projects are characterized by high-risk and high-payoff ("Our Research," n.d.). As we have discussed, real options are more valuable when the risks and uncertainties influencing R&D projects are higher. These high-risk cases, therefore, provide a picture of the dramatic effects of real options in defense R&D projects. Third, since these projects are underway, they are well-known by practitioners. Therefore, the analysis of these cases facilitates the reader's comprehension of the value of real options in defense R&D projects.

2. Design of the Cases

To enhance the reader's understanding of the use of real options, DARPA cases are simplified to a limited number of decision nodes and chance events. As agreed by scholars, for practical purposes, complex cases should be simplified to "keep the analysis tractable" (Kemna, 1993, p. 260) and relay the insights of this analysis. As Triantis (2005) discusses, the use of simple cases rather than complex models is characterized by a tradeoff between practicality and precision. While complex models provide more realistic and academically more accurate patterns at the expense of practical execution, simplified models offer easy-to-implement patterns but lack such accuracy (Triantis, 2005). Considering the purpose of this study—which is to present the benefits of using real options in defense R&D projects—practicality and simplicity are preferred over accuracy. Moreover, as opposed to complex techniques in real options that are poorly executed by practitioners, simplified models provide decision makers with useful techniques that show how to incorporate managerial flexibility and exploit uncertainties. As a result of these benefits, simple cases are used in this study.

As discussed in the first chapter, defense R&D projects are crucial for national security and they are undertaken confidentially. These aspects require that the details of the projects are kept classified. Therefore, the cases analyzed in the thesis are in conformity with confidentiality requirements. The background information of the cases is gathered from open sources, which provide unclassified information. Moreover, fictional data is used for the problem definition and data, including the monetary values and probabilities that are necessary to evaluate the cases. Once the cases are built, they are analyzed in light of the NPV and the DTA techniques examined in the following sections.

B. NET PRESENT VALUE ANALYSIS

Many scholars and practitioners have regarded NPV analysis as a traditional yet broadly used method in project valuation and capital budgeting (e.g., Copeland & Antikarov, 2001; Brealey et al., 2008; Makropoulou, 2011; Trigeorgis, 1996). According to Brealey et al. (2008), "75% of firms always, or almost always, calculate net present value when deciding on investment projects" (p. 117). The widespread application of NPV demonstrates that most of the managers still rely on traditional methods that do not account for managerial flexibility in capital budgeting. When managers do not want flexibility, though, NPV analysis is the most effective tool to value investment projects for which other traditional project appraisal methods—such as the accounting/average rate of return, the payback period, and the internal rate of return—are regarded as inferior (Trigeorgis, 1996). The NPV method is analyzed in this thesis because it is not only a commonly used valuation and decision making method, but also a building block for evaluating decision trees and valuing real options.

1. The Net Present Value Rule

The NPV rule states that a project should be accepted if it has a positive net present value (Brealey et al., 2008). Conversely, a project should be rejected if it has a negative net present value. The mechanics of this rule are simply defined by Dixit and Pindyck (1994) in three steps. First, determine the present value of the flow of profits (positive cash flows, or cash inflows). Second, calculate the present value of the flow of investments (negative cash flows, or cash outflows). Finally, invest in the project if the difference between the two is positive (i.e., if the investment has a greater-than-zero NPV). To calculate the present values of positive and negative cash flows, decision analysts should discount future cash flows at a pre-specified rate (the discount rate) to account for the time value of money (Brealey et al., 2008). The following equation, which is adapted from Trigeorgis (1996, p. 31), summarizes the NPV calculation:

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - \sum_{i=0}^{T} \frac{O_t}{(1+r)^t} \tag{1}$$

for

r: Risk-free interest rate

C_t: Cash inflow in year t

O_t: Cash outflow in year t

T: Project life in years

The NPV rule has some important advantages that tempt managers to use it so extensively. First, the NPV rule takes the time value of money into consideration by discounting the expected cash flows to today’s dollars (Brealey et al., 2008). As opposed to, for instance, the payback period method, the NPV accounts for the opportunity cost of money, which is a crucial quality for investment decisions that span many years. Second, the NPV rule provides managers with a simple formula that demands a small number of inputs—i.e., the cash flows and the discount rate of a project (Brealey et al., 2008). In this sense, managers can work the NPV rule without being overwhelmed with complex estimations and calculations. Third, since the present values of projects are calculated in today’s dollars, managers can add up and compare the project values (Brealey et al., 2008). This feature is reasonably useful for managers, since they can easily bundle the projects together or dismantle them for decision-making purposes. However, this last characteristic is also open to misuse; for instance, projects with negative NPV can be bundled with other projects, resulting in a positive total NPV.

2. Limitations

Although public and corporate decision makers widely use the NPV rule, it is commonly criticized for its two essential limitations: it does not account for flexibility, and it adjusts for risk by increasing the discount rate. First, the NPV approach fails to account for managerial flexibility to revise and alter future decisions (Brealey et al., 2008; Trigeorgis, 1996). The NPV handles the project from a now-or-never standpoint by comparing investing today with investing never (Dixit & Pindyck, 1995). Additionally, the NPV rule implicitly assumes that decision makers will manage projects passively with no intervention for future alternatives that may be created by the initial decision but are uncertain given the data at hand (Beninga & Tolkowsky, 2002). Once the plan is finalized and the decision is made, management has no initiative to interfere, but to wait and see the outcome. The NPV, therefore, overlooks future possibilities and takes into account only a “fixed scenario” in which an investor invests in a project and generates certain cash flows during the lifetime of the project (Dixit & Pindyck, 1995, p. 107). This limitation obstructs the real value of the project, thus undervaluing the investment decision.

The inability to account for managerial flexibility is particularly apparent in long-standing projects, which are characterized by high uncertainty and risks (Newton et al., 2004). Defense R&D projects, as discussed in the first chapter, abound with project-specific risks and should be handled with flexible methods. Nevertheless, the NPV approach does not provide such flexibility and ignores many real options inherent in defense R&D projects. Under uncertainty, managers would want to possess real options as strategic assets. Due to the asymmetric nature of real options—benefiting from favorable changes but avoiding unfavorable ones (Copeland & Antikarov, 2001)—managers can reduce losses and increase gains by proper interventions (Yao & Jaafari, 2003). They may want to wait until future uncertainties unfold. After initial investment, they may want to expand the R&D project if it turns out successful; or contract and even abandon a project altogether if unsuccessful. Projects that provide managers with these kinds of real options are more valuable compared to those that do not. The NPV approach, however, ignores these real options.

Second, the way the NPV approach handles uncertainty is problematic. The NPV approach assigns a discount rate for every cash inflow and outflow of the project. When the risk of the investment—particularly the volatility of cash inflows—is considered to be larger than normal, the decision maker increases, or adjusts, the discount rate, which is the most common practice (Amram & Kulatilaka, 2000). This practice is called the "risk-adjusted-discount-rate (RADR) approach" and it accounts for both the time value of money and the risk—internal and external—associated with the investment (Trigeorgis, 1996). In this approach a risk premium $p`$ is added to the risk-free interest rate r to calculate k (the RADR) and k is inserted into Equation 1 instead of r to compensate for risk. The RADR version of the NPV thus becomes:

$$NPV = \sum_{t=1}^{T} \frac{C_t}{(1+k)^t} - \sum_{i=0}^{T} \frac{O_t}{(1+k)^t} \tag{2}$$

This approach is problematic for valuing defense R&D projects, which are extremely risky long-term investments. Since the risk premium $p`$ increases proportionate to the level of risk associated with the investment, NPV requires very high RADR for defense R&D projects. Accordingly, high RADR leads to high discounts and erroneous undervaluation of the R&D projects (Steffens & Douglas, 2007). This effect further intensifies with lengthier project life, since a longer time horizon means higher discounts (Perlitz et al., 1999). In this regard, the RADR approach is counterintuitive to real options thinking and to the asymmetric nature of real options. In the investments with real options, high risk and volatility create opportunities for managers, who can benefit from positive outcomes while avoiding negative results by intervening as the uncertainty resolves. Moreover, since higher discount rates undervalue the real worth of remote cash flows, the NPV method creates myopia in evaluating long-term investment projects (Dixit & Pindyck, 1995). This myopic effect prevents the managers from properly evaluating the long-term influences of current decisions, thus potentially deviating from strategic aims of the organization.

As a result, because of its failure to integrate flexibility into investment decisions and the drawbacks of the RADR approach, the NPV is not a practical tool for long-term risky projects. Therefore, the NPV approach, by itself, fails to evaluate the real value of the defense R&D projects, thus presenting fundamental problems for strategic decision making. However, the NPV concept and its formula constitute the foundation of the decision tree analysis and real options valuation.

C. DECISION TREE ANALYSIS

Commonly used in capital investment decision making, the decision tree analysis deals with uncertainty and complexity that the NPV fails to account for. The DTA method helps managers construct the investment decision as series of decision points and chance events within a hierarchy that spans the lifetime of the project (Trigeorgis, 1996). Decision trees improve decision making by mapping out all relevant decisions and chance events, associated risks and probabilities, and cash flows in a comprehensible way (Magee, 1964a). In this regard, the DTA allows managers to follow multiple decision paths and visualize the project risks and the effects of future decisions on the project. As opposed to the NPV analysis, which disregards future choices by solely focusing on the initial decision, the DTA urges managers to consider the investment decision in the light of operational strategy and identify the relationships between subsequent decisions (Trigeorgis, 1996). This versatile nature of the DTA, therefore, provides a useful analytical and visual decision support tool for managers.

1. Building Decision Trees

Managers have long been using the DTA method as a common practice to model and value real options in capital budgeting, even before the real option concept was clearly recognized (Brealey et al., 2008). Thanks to its versatile nature, the decision tree is a very functional tool to imbed real options into investment decisions and to value them. Since this thesis uses decision trees to integrate and value real options in defense R&D projects, I find merit in reviewing some key concepts of the DTA method and its applicability in defense R&D. Magee (1964a; 1964b), by using complex but comprehensible examples, unambiguously illustrates the construction and use of decision trees in decision making and in capital investment. Magee (1964b) lists the steps to build decision trees for capital investments:

1. Recognizing the problem and identifying the alternatives,

2. Designing the tree,

3. Acquiring the necessary data,

4. Evaluating the alternatives and solving the tree.

The first step in the DTA method is to identify the problem, existing alternatives, possible courses of actions, and uncertainties affecting current and future decisions (Magee, 1964b). Managers may not spot all future probabilities, but they may conduct a good deal of work that in turn reinforces the plausibility of the investment decisions (Magee, 1964b). For defense R&D projects, this step requires a detailed analysis of the investment decision by experienced managers. Decision makers should comprehend the nature of the R&D project, analyze relevant risks, and determine alternative courses of action under uncertainties before laying out the decision problem.

The second step in constructing a decision tree is its physical design. An important issue to resolve before constructing the tree is the level of detail and the timespan that will be covered in its design (Magee, 1964b). As Magee (1964b) states, it is crucial to hit the right detail level that "permits executives to consider major future alternatives without becoming so concerned with detail and refinement that the critical issues are clouded" (p. 82). In decision trees, analysts should not try to identify all the events and the decisions; rather, they should lay out those that are significant to the decision maker and have impacts that need evaluation (Magee, 1964a). Therefore, the detail level presented in the decision trees for defense R&D should be sufficient enough to help managers make reasonable decisions and, at the same time, simple enough to prevent decision makers from being overwhelmed in complexity. In terms of the timespan to be covered in decision trees, Magee (1964b) states that it depends on the particular project. He claims that "the practical time span or 'horizon' to consider should extend at least to the point where the distinguishing effect of the initial alternative with the longest life is liquidated, or where, as a practical matter, the differences between the initial alternatives can be assumed to remain fixed" (p. 82). The timespan for defense R&D projects, therefore, hinges significantly on the characteristics of the project—e.g., expected completion period, expected payoffs, associated risks and uncertainties, and desired level of flexibility. Accordingly, there is no prescribed level of detail and appropriate timespan for the DTA of defense R&D projects in a general sense; every project should be considered within its own context.

As explained by Magee (1964a), a typical decision tree consists of a series of nodes and branches. Squares signify decisions, and circles signify chance events. The branches stemming from decision nodes represent courses of actions or decisions; while the branches from chance nodes represent alternative outcomes of these chance events. From left to right, a decision tree splits into paths and finally reaches to the rightmost, or terminal, branches, which are symbolized by triangles. Each complete course from the start to the end is associated with a payoff, which is displayed at the end of each terminal branch.

The third step requires the analyst to obtain the data needed. This data includes the payoffs of each complete course and the probabilities of the uncertain alternative outcomes. As stated by Magee (1964b), the standard investment decision is made considering the maximization of expected wealth, which is calculated as the NPV of expected cash flows. The defense R&D, however, is not evaluated in a corporate environment, and is not necessarily aiming at wealth maximization. As discussed in the first chapter, the main objectives of defense R&D for the country include national security, deterrence, and military competition. As a result, these objectives—or the expected outcomes of defense R&D projects—are generally indicated as non-monetary benefits. Although accurately measuring the defense R&D output in monetary terms is a challenge for decision makers, a significant amount of effort can be made to assess proposed capabilities and cost estimates (Hartley, 2011). To conduct a DTA, the analyst, therefore, should convert all costs and benefits into dollar values, such as the case in cost benefit analysis (Boardman, Greenberg, Vining, & Weimer, 2006). Since cost benefit analysis is out of the scope of this thesis, the methods for this conversion are not covered. The cases in this thesis provide the monetary values of these payoffs.

Analysts can find the probability estimates of uncertain alternatives either objectively from research or subjectively from intuitive judgment (Keeney, 1982; Magee, 1964b); or from a combination of both. Considering the challenges with defense R&D projects—uniqueness, long project life, uncertain outcomes, and risks and uncertainties regarding the research and development process—these probability estimates are less likely to be derived from objective research. Therefore, incorporating subjective beliefs and preferences in defense R&D decision making is very important.

A significant problem with the probability estimation stems from the nature of the probability distribution. As Trigeorgis (1996) explains, in DTA, uncertainties and alternatives are defined as discrete points in time—such as the alternative outcomes of rolling a dice. However, in many practical cases, these uncertainties and alternatives show continuous distribution, where a range of answers is possible—such as the case in daily temperatures (Magee, 1964b). To handle this issue, a decision analyst can divide the continuous distribution into discrete slices to incorporate the data into the decision tree. According to Magee (1964b), although this approach oversimplifies the situation, it is often sufficient and does not lead to serious errors. To illustrate, think of a defense analyst who wants to use in the DTA the success level of an R&D project as a chance event. Consider the analyst uses a set of criteria that measures the success of the project by ultimately assigning a score between 1 and 100. Since the result of this evaluation can be anywhere within this range, the analyst should slice the score into meaningful sets. For instance, a score over 80 may be regarded as successful and mean a greenlight for the next stage. A score between 60 and 80 may indicate that additional development process is necessary. Finally, a score below 60 may be regarded unsuccessful, and decision makers may choose to terminate the R&D project altogether. Clearly, the analyst now has three distinct paths for the chance event to be used in the decision tree. The analyst can also assign the respective probabilities of these paths by assigning the continuous probability distribution of the success score to these ranges.

The final step in the DTA method is to evaluate the alternatives by comparing the outcomes of different decisions. Here, the DTA does not promise to give decision makers the exact answer to an investment opportunity—as no such decision support tool can (Keeney, 1982). Rather, it helps managers determine the course of action with the highest expected payoff, given the information at hand (Magee, 1964a). The big question for the managers is to decide what to do today. To answer this question, the decision maker should start his analysis by first thinking what he would do if he were at the future decision point (Brealey et al., 2008). This involves putting a monetary value—or a position value—to each subsequent decision points (Magee, 1964a). This process is called the “rollback” (Magee, 1964a) concept and requires solving the decision tree by analyzing from right to left and assigning values to each decision node (Steffens & Douglas, 2007). The logic of this aspect is that a decision is regarded optimal provided that following decisions are optimal (Yao & Jaafari, 2003). Therefore, the analyst should make the current decision in light of its effects on future decisions.

As a result, the DTA combines the NPV analysis with a clear view and analysis of relevant decisions and chance events (Magee, 1964a). The DTA approach helps managers map out investment projects with their respective uncertainties, decision points, alternatives, associated probabilities, and costs and benefits. With its simplicity and clarity, along with providing clear connections among all relevant decisions, the DTA method is an extremely useful tool for defense R&D managers.

2. Criticism and Discussion

Although the DTA provides several benefits for defense R&D projects, it is criticized mainly in two ways. Reviewing these critiques is important to respond and validate the use of the DTA method over the ROV approach to model and value real options in defense R&D projects.

The first criticism is about the possible complexity of decision trees. For instance, Trigeorgis (1996) claimed that the DTA can turn into a “decision-bush analysis” (p. 66) when it is applied to real investment decisions. Likewise, Brealey et al. (2008) stated that decision trees are inclined to grow very complex relatively quickly, thus overwhelming decision analysts. These scholars likened decision trees to grapevines, in that “[t]hey are productive only if they are vigorously pruned” (p. 293). This critique may hold true for earlier times when no computerized program existed. Today, however, there is readily available software that can handle extremely complex decision trees relatively easily. Moreover, considering that defense R&D projects are inherently complex and are undertaken in highly uncertain conditions, using oversimplified real life models may not reflect the real value of the projects. The unique nature of defense R&D projects necessitates customized decision trees at specific complexity rather than rigid ROV formulas and models that work with market inputs. In this sense, the DTA approach allows managers to properly model and value defense R&D projects.

The second criticism of DTA focuses on determining the proper discount rate (e.g., Brealey et al., 2008; Lander & Pinches, 1998; Trigeorgis, 1996). These scholars, while praising the use of the ROV approach, criticize using a discount rate that is kept constant across the timespan of the project. For them, constant rate implies that project uncertainties are resolved constantly and continuously, which is impractical since the risks being exposed are constantly shifting. This criticism may be reasonable for projects that are extensively exposed to market risks; however, it rarely holds true for projects with private risks (Steffens & Douglas, 2007). Several scholars agree that a risk-free interest rate should be used to value investment projects that are dominated by private risks and in which market uncertainty is irrelevant (e.g., Borison, 2005; De Reyck, Degraeve, & Vanderborre, 2008; Smith & McCardle 1998). Moreover, since the discount rate also accounts for the opportunity cost of capital, the use of a risk-free rate for defense R&D projects that are funded by government funds makes sense. Therefore, the risk-free interest rate is used in this study. Besides, the constant risk-free rate is among the ROV assumptions to value real options. In this sense, the criticism of ROV supporters regarding the limitation of constant discount rate pays back with its own coin.

Another important point to address in this discussion is that the discount rate critique implicitly assumes that decision analysts will increase the discount rate to compensate for risks. This implies that the higher the risk, the higher the discount rate. As I have discussed in the previous section, the RADR approach is one of the essential limitations of the NPV technique in valuing defense R&D projects. Discounting expected future values at higher discount rates undervalues investment decisions and acts counter to the idea of real options. In evaluating defense R&D projects with the DTA approach, decision makers should integrate risks and uncertainties into their analysis with real options thinking by properly defining alternatives and probabilities, building a decision tree, and incorporating managerial flexibility with relevant real options.

In sum, the DTA approach was widely used to integrate flexibility into investment decisions even before real options as a term was realized. The DTA approach provides a versatile evaluation method that can easily incorporate and value real options relevant to defense R&D projects. Since the criticisms of the method (i.e., possible complexity and choosing the proper discount rate) are misconceptions, DTA proves to be a better method than the ROV method in modeling and valuing real options in defense R&D projects.

D. CHAPTER SUMMARY AND CONCLUSION

In this thesis, I employ a mixed methodology, integrating the DTA approach with case studies, to build simple real option models. This methodology utilizes the benefits of the case study method and the DTA approach to answer the research questions effectively. Benefits of the case study method stem from its practicality in analyzing simplified defense R&D cases to illustrate the use of real option concepts, which are applicable to a broader range of defense R&D projects. And, the DTA approach feeds into these benefits by providing a versatile approach to model the decision problems and to value the real options in defense R&D projects. Although the NPV approach establishes the fundamental principles of the DTA, the NPV approach on its own fails to account for flexibility; therefore, it is not a valuable capital budgeting tool for defense R&D projects. The criticism of DTA, though, is groundless, since it proves to be a better approach than the NPV and the ROV methods in defense R&D decision making. Moreover, simplified models are preferred over complex ones in that they help practitioners track the analysis and comprehend the value of flexibility in defense R&D projects. In light of the methodology described here, the next chapter analyzes the defense R&D cases.

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IV. ANALYSIS AND EVALUATION

This chapter employs the methodology described in the previous chapter to analyze and evaluate three continuing DARPA R&D projects to model options to defer, abandon, and expand. These DARPA projects are characterized by high risks and high payoffs, thus clearly illustrating the effects of real options in defense R&D projects. I analyze these three cases in the following order. First, I introduce each case and provide background information from open sources to outline the current situation. Second, I present a hypothetical problem and fictional data to frame the analysis. Third, I build the decision tree without flexibility—i.e., the respective real option—and calculate the NPV of the project. For NPV calculations, I take the risk-free rate as 5 percent. Fourth, I incorporate the particular real option into the DTA and calculate the NPV of the project with the option. This NPV, along with that in the third step, produces the value of the respective real option. Lastly, I provide a brief evaluation of the effect of the real option on the particular case. Following the analysis and the evaluation of the cases, I discuss the limitations of the analysis conducted in the thesis. Finally, I close the chapter with a brief evaluation and conclusion.

A. CASE 1: OPTION TO DEFER

The first case, DARPA's Communications Under Extreme RF[2] Spectrum Conditions (CommEx) program, demonstrates an option to defer, which provides the holder an option to wait for a certain amount of time until certain uncertainties are resolve. The objective of the CommEx is to enhance the communication of friendly forces within a congested jamming environment by suppressing enemy jamming with "adaptive interference suppression" (Phoel, n.d.). The program is currently in its technology development phase.

[2] Radio frequency

1. Background

DARPA awarded CommEx contracts to BAE Systems Company in 2011 to develop adaptive communication technologies under intense jamming, which blocks the RF receivers of military aircraft (Keller, 2011). The company worked on the project until 2015, when it demonstrated the benefits of the CommEx in a laboratory environment ("Communications Under," n.d.). Currently, the test and demonstration phase is nearly finalized. The CommEx technology is planned as an upgrade to the Link 16 air-to-air data-exchange network, which is used by several nations (Pellerin, 2016). According to the DARPA, the CommEx will fix the vulnerability of the Link 16 network to enemy jamming (Skowronski, 2016). If the program passes the testing phase, the CommEx will be installed on aircraft to upgrade the Link 16 network.

2. The Problem and the Data

Let us assume the CommEx passed all tests and proved to overcome every possible interference known today. DARPA thinks that the system is ready to be installed on the aircraft fleet for a cost of $145 million. However, let us also assume intelligence is received that an adversary has been developing a jammer that may be capable of blocking the CommEx. The adversary and its allies will start using the new jammer two years from now. According to the program manager, the new jammer will have a 20 percent chance of blocking the CommEx. This means that the CommEx will still communicate, despite the jammer, with an 80 percent chance of success. If the adversary's jammer blocks the CommEx, the payoff will be −$195 because the CommEx should be detached from the aircraft and subject to further development processes. If the jammer cannot block the CommEx, the payoff will be $240 million.

3. The Design of the Decision Tree

The program manager has a decision to make today: finalize the development process and install the CommEx or do not install the CommEx. The decision tree without flexibility (i.e., option to defer) can be constructed as in Figure 1.

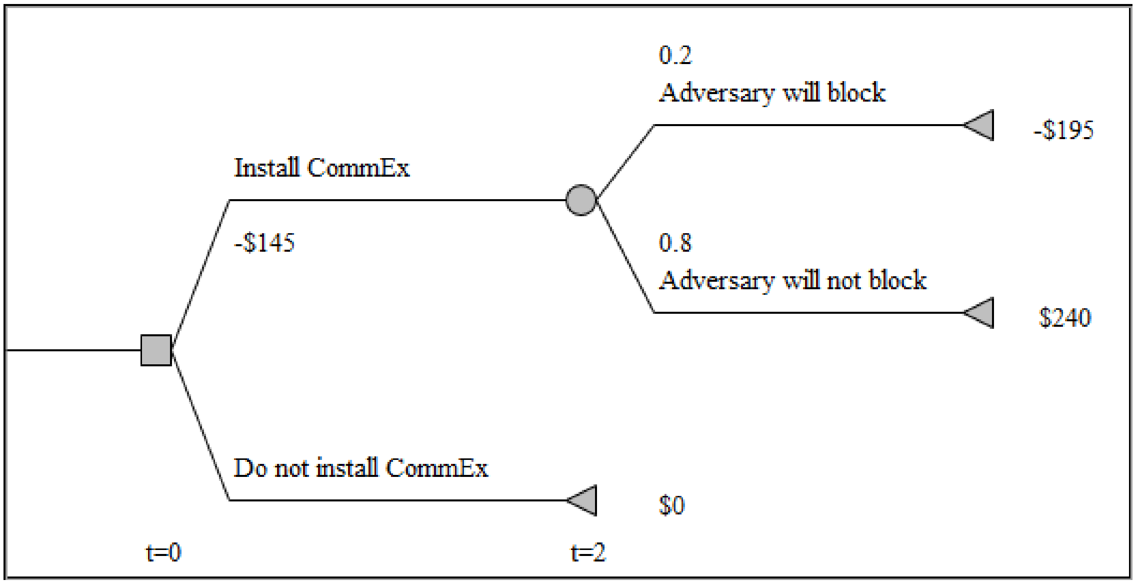

Figure 1. CommEx Program Decision Tree without the Option to Defer.

Once the decision tree with the relevant data is laid out, we can solve the tree. The problem for the program manager is to decide which alternative to choose. His decision should be the alternative with highest expected NPV. The NPV of not installing the CommEx is \$0. The NPV of installing the CommEx is:

$$NPV = -145 + \frac{(0.2)(-195) + (0.8)240}{(1+0.05)^2} = -\$6.2 \text{ million}$$

In this case the net value of installing the CommEx is −\$6.2 million. Since not installing the program is worth \$0, the program manager will choose not to install the program. Therefore, the NPV of the CommEx program without flexibility is \$0. This naïve DTA undervalues potential flexibilities managers can benefit from. The analysis, therefore, can be enhanced by adding an option to defer to the tree.

4. Integrating the Option to Defer

Consider the program manager wants to wait two years and see the capabilities of the adversary's jammer. After evaluating the jammer, he will decide whether to insert the CommEx or not. BAE Systems agrees to install the CommEx two years later for a cost of \$160 million. The decision tree with the option to defer becomes as the one in Figure 2.

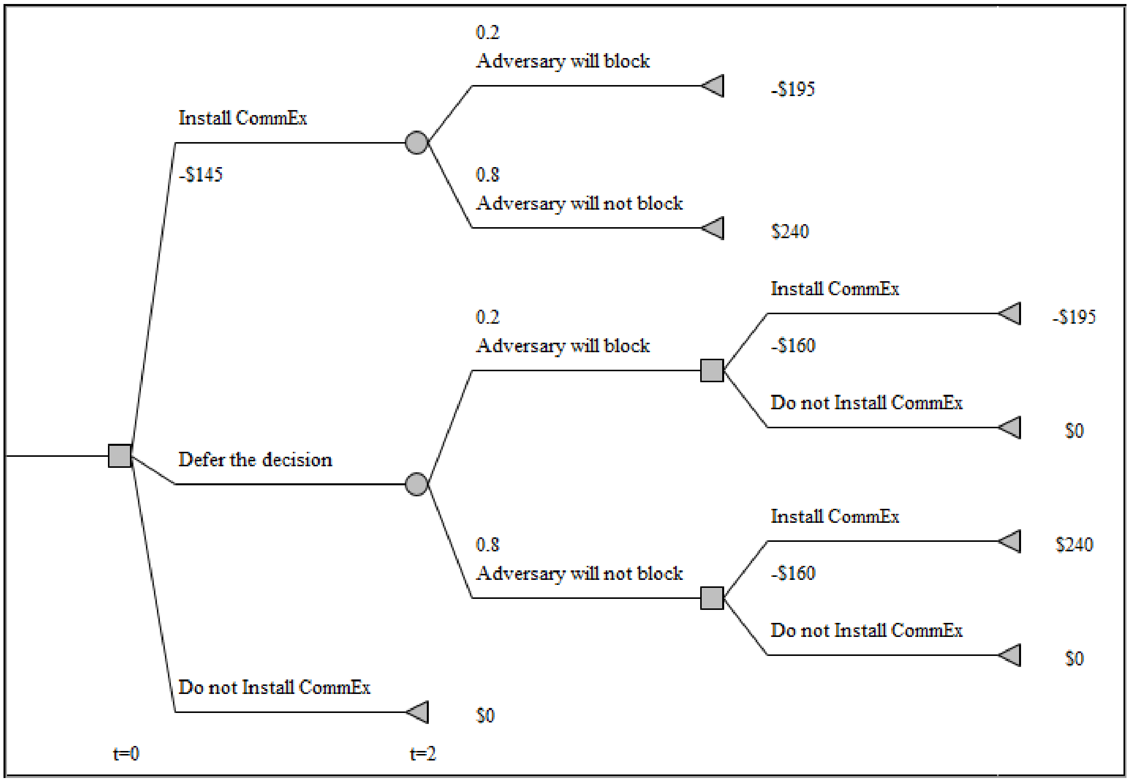

Figure 2. CommEx Program Decision Tree with the Option to Defer.

The problem for the program manager is to decide which alternative to choose today. To do that, he needs to know what he would do next year. Therefore, we solve the decision tree from right to left, starting from the decisions two years from now. After waiting two years and evaluating the adversary jammer, if the program manager understands that the adversary will have a capability to block the CommEx, he will decide not to install; because installing will cost –$355 (–$160 – $195) million, whereas not installing will have no cost. Likewise, if it turns out that the adversary will not block, the program manager will choose to install the CommEx. Installing the CommEx will have $80 ($240 – $160) million benefits, whereas not installing will have none. Therefore, the NPV of deferring the installation of the CommEx is:

$$NPV = \frac{(0.2)0 + (0.8)80}{(1+0.05)^2} = \$58 \text{ million}$$

Now, the program manager's decision today becomes deferring the decision to install the CommEx. Therefore, the net value of the program becomes $58 million. The value of the option to defer can be calculated as the difference between the NPVs with and without the option, viz.: $58 − $0 = $58 million.

5. Results

The case illustrates the value of waiting for uncertainties to be resolved before making important defense R&D investment decisions. The option to defer the installation of the CommEx changed the net project value from negative to a considerably positive figure, a net increase amounting to $58 million. This amount is also the value of the option to defer the decision.

B. CASE 2: OPTION TO ABANDON

The second case, DARPA's Anti-Submarine Warfare (ASW) Continuous Trail Unmanned Vessel (ACTUV) project, illustrates an option to abandon, which is very typical in sequential defense R&D projects. The ACTUV program develops an unmanned vessel that is capable of tracking diesel electric submarines in open seas (Littlefield, n.d.). The prototype vessel is currently being tested by DARPA.

1. Background

The ACTUV program started in 2010 (Cahn, 2016) and was planned as four consecutive phases: concept exploration, design, construction, and testing (Walsh, 2016). The contractor of the program, Leidos Inc., designed and built the ACTUV as a 132 foot long trimaran, which is required to traverse long distances across the ocean without any maintenance or crew member on board (Cahn, 2016; Walsh, 2016). The ACTUV, also called as the Sea Hunter, was christened on April 7, 2016, the date that signifies the start of the two-year long testing period ("Enjoy the Silence," 2016). As the first milestone of this testing phase, the ACTUV passed all performance objectives, such as speed, balance, maneuverability, and fuel efficiency ("Leidos Completes," 2016). However, the most important aspect of the ACTUV is its unmanned safe navigational capability that is in compliance with the International Regulations for Preventing Collisions at Sea (COLREGs) ("Enjoy the Silence," 2016). Although initially designed for ASW missions, the ACTUV, if COLREGs-compliant, can be extended to other missions, such as mine countermeasures and intelligence (Walsh, 2016). Provided the ACTUV passes the testing phase, DARPA will transfer the program to the Navy.

2. The Problem and the Data

Let us assume the program manager wants to evaluate the project at the start of the testing phase, on April 2016, to make a decision whether or not to continue testing. If he chooses not to continue testing, the payoff will be \$0. If he continues with the testing, the two-year long tests will cost \$30 million. Based on his analysis, he identifies three possible outcomes at the end of the two-year testing period. According to the program manager, there is a 60 percent chance that the testing result will be excellent, a 30 percent chance that it will be good, and a 10 percent chance that it will be poor. An excellent result signifies that the ACTUV is flawlessly compliant with the COLREGs, and it can be extended to other missions. The payoff for this outcome is calculated as \$50 million. A good result means that, except for some flaws, the ACTUV is compliant with the COLREGs, and the program can continue for ASW missions, but cannot be extended to other missions. The payoff for this chance event is \$35 million. Finally, a poor result indicates that the program has significant flaws, which stem from its design and construction. In this case, DARPA should revise the design and construction of the ACTUV, incur additional money outlay, and require several more years for the program to mature. The payoff is calculated as −\$90 million.

3. The Design of the Decision Tree

The decision the program manager should consider today can be framed as starting the testing phase for the ACTUV or not. The decision tree without flexibility, i.e., option to abandon, appears in Figure 3.

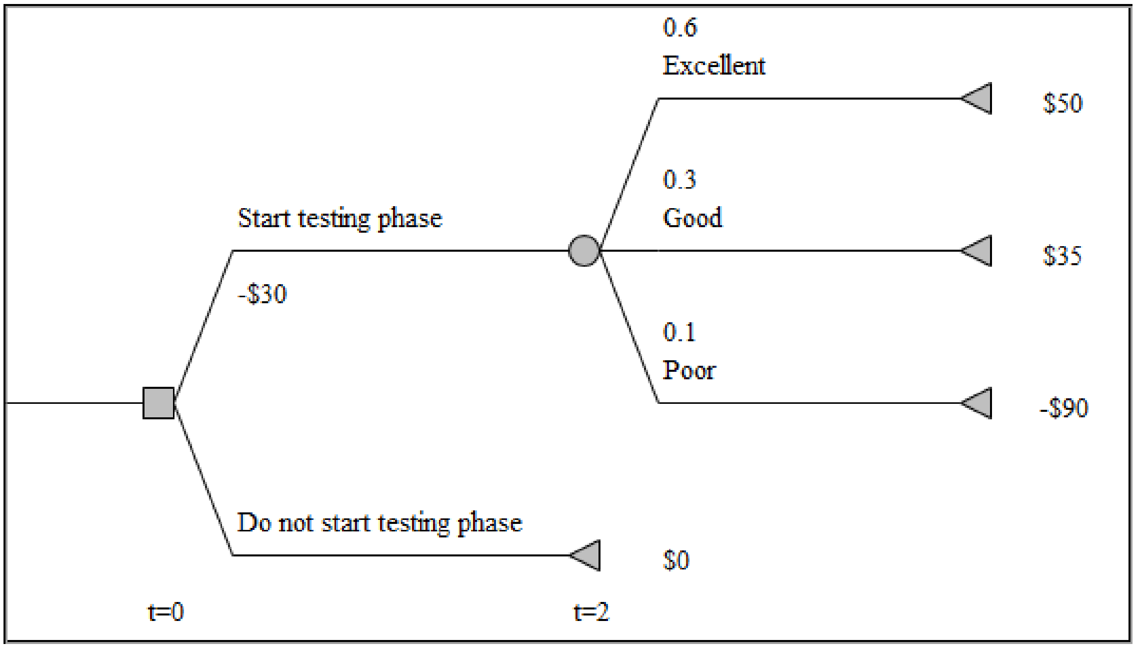

Figure 3. ACTUV Program Decision Tree without the Option to Abandon.

To decide on which alternative to choose, the program manager should calculate the expected NPVs of the alternatives. The NPV of not starting the testing phase is $0. The NPV of starting the testing phase is:

$$NPV = -30 + \frac{(0.6)50 + (0.3)35 + (0.1)90}{(1+0.05)^2} = -\$1.4 \text{ million}$$

As a result of this naïve DTA, the program manager will decide not to start the testing phase, since the NPV of starting the testing phase is calculated as −$1.4 million. This signifies that the NPV of the program without flexibility is $0. However, adding an abandonment option has a significant effect on this decision and the value of the program.

4. Integrating the Option to Abandon

Assume the program manager wants to secure a contract that allows DARPA to abandon the project if the test results turn out to be poor. Rather than bearing the additional burden in the worst possible outcome, DARPA will choose to terminate the program. The decision tree with the option to abandon becomes as the one in Figure 4.

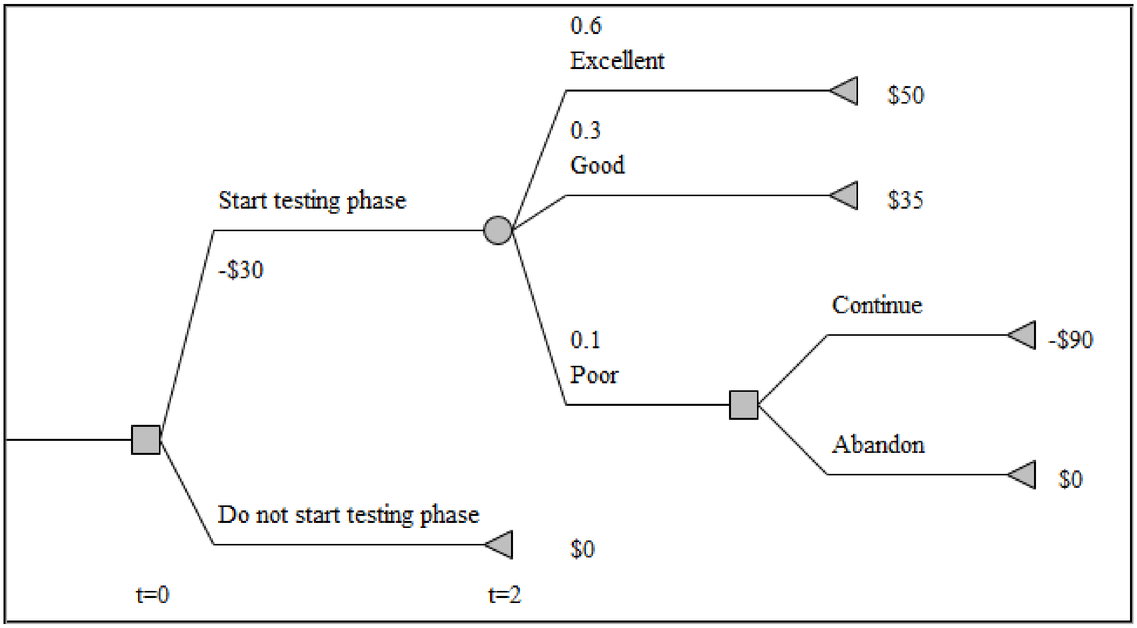

Figure 4. ACTUV Program Decision Tree with the Option to Abandon.

To find the optimum decision today, we solve the decision tree starting from the rightmost decision. In the event that the test result is poor, the program manager will choose to abandon the project, rather than incurring a $90 million cost. The payoff of the poor outcome thus becomes $0. The NPV of starting the testing phase becomes:

$$NPV = -30 + \frac{(0.6)50 + (0.3)35 + (0.1)0}{(1+0.05)^2} = \$6.7 \text{ million}$$

Since not starting the testing phase has $0 outcome, the NPV of the ACTUV becomes $6.7 million. This increase is due to the abandonment option that protects against additional losses. The option to abandon is calculated as $6.7 – $0 = $6.7 million.

5. Results

This case demonstrates that an option to abandon can dramatically increase the NPV of a defense R&D project. With the abandonment option that prevents additional spending in the event of the poor test result, the initial decision of the program manager has changed. The change in the net value of the program also denotes the value of the option to abandon, i.e., $6.7 million.

C. CASE 3: OPTION TO EXPAND

The third case, DARPA's Aircrew Labor In-Cockpit Automation System (ALIAS) program, illustrates an option to expand, which is common in R&D projects whose scale may be increased depending on the outcome of the initial application. The ALIAS devises an adjustable drop-in kit that would decrease the need for onboard crew by providing increased levels of automation to Army helicopters (Patt, n.d.). The ALIAS aims to leverage the existing automation systems to execute a complete mission from takeoff to landing, while increasing mission performance and safety (Patt, n.d.). The program is currently in development phase.

1. Background

Although the ALIAS program started in 2015—when DARPA awarded a contract to Sikorsky Aircraft Company as the first phase—the technology behind the ALIAS goes back to Sikorsky's autonomous research helicopter launched in 2013 ("DARPA Awards ALIAS," 2015). After making modifications to its technology, Sikorsky demonstrated in May 2016 an autonomous flight of a commercial helicopter controlled by a tablet device ("Sikorsky Successfully," 2016). Following this test, Sikorsky is awarded the second phase of the program, in which the company focuses on enhancing human interfaces and ensuring the transition of the system to additional aircrafts ("Sikorsky Successfully," 2016). The ultimate aim of the project is to transition the ALIAS technology to DOD utility helicopters.

2. The Problem and the Data

Let us assume that at the end of the second phase, the ALIAS is proved to be transferrable to other utility helicopters. Additionally, the human interface is enhanced to provide an easy to use, safe, and reliable system. The ALIAS is now ready to be installed in the entire helicopter fleet. However, the program manager has suspected that the flight crew, which has had several years' experience with the existing systems, may have low levels of acceptance for the ALIAS. A dramatic change to an automation system may backfire and produce undesirable consequences. The program manager evaluates that the feedback data from the crew will be provided after one year of hands-on experience on several types of aircraft. Consequently, he designates two alternatives: install the ALIAS to either the entire fleet inventory for a cost of $250 million or to one-tenth of the inventory for a cost of $65 million. If the ALIAS is installed to the entire fleet, there is a 70 percent chance that the human acceptance level will be high. In this case, the payoff will be $850 million. However, there is a 30 percent chance that the acceptance level will be low. This means that the technology will not be as beneficial and the payoff will be $300 million. As to the other alternative, where the ALIAS is installed in one-tenth of the fleet, which is a sample of the entire aircraft, the expected human acceptance levels are estimated to be the same. If the acceptance level is high, the payoff will be $100 million. Conversely, if the acceptance level is low, the payoff will be $40 million.

3. The Design of the Decision Tree

Today's decision for the program manager is installing the ALIAS either to the entire fleet or to one-tenth of the fleet. With the data at hand, a decision tree without flexibility, i.e., option to expand, can be built as in Figure 5.

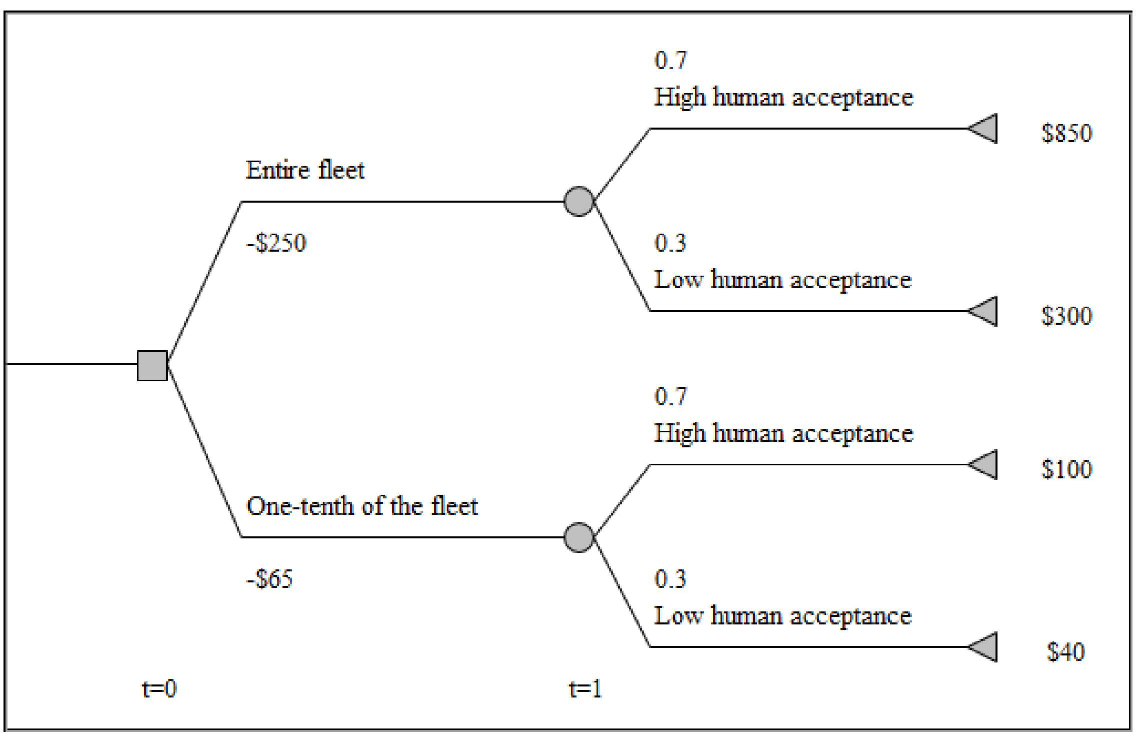

Figure 5. ALIAS Program Decision Tree without the Option to Expand.

The program manager should decide which alternative to choose today. His decision will be the alternative with highest expected NPV. The NPV of inserting the ALIAS to the entire fleet is:

$$NPV = -250 + \frac{(0.7)850 + (0.3)300}{1 + 0.05} = \$402.4 \text{ million}$$

The NPV of inserting the ALIAS to one-tenth of the fleet is:

$$NPV = -65 + \frac{(0.7)100 + (0.3)40}{1 + 0.05} = \$13.1 \text{ million}$$

Therefore, the program manager will choose to insert the technology to the entire fleet. In this case, the value of the program is calculated as $402.4 million. However, this is an extremely naïve DTA that ignores the option to expand and undervalues the R&D project.

4. Integrating the Option to Expand

Let us assume the program manager wants to secure an expansion contract that allows DARPA to expand the ALIAS to the entire fleet provided the human acceptance level is high. In this case, the DARPA program manager will have an additional decision point where he may choose to expand the program and install the ALIAS technology to the rest of the helicopter fleet. The cost for this expansion will be $200 million. If the program is expanded, human acceptance levels will again be evaluated one year later. This time there is a 90 percent chance that the acceptance level will be high, with a payoff of $1,050 million. There is a 10 percent chance that the level will be low, with a payoff of $300 million. The decision tree with the option to expand can be designed as the one in Figure 6.

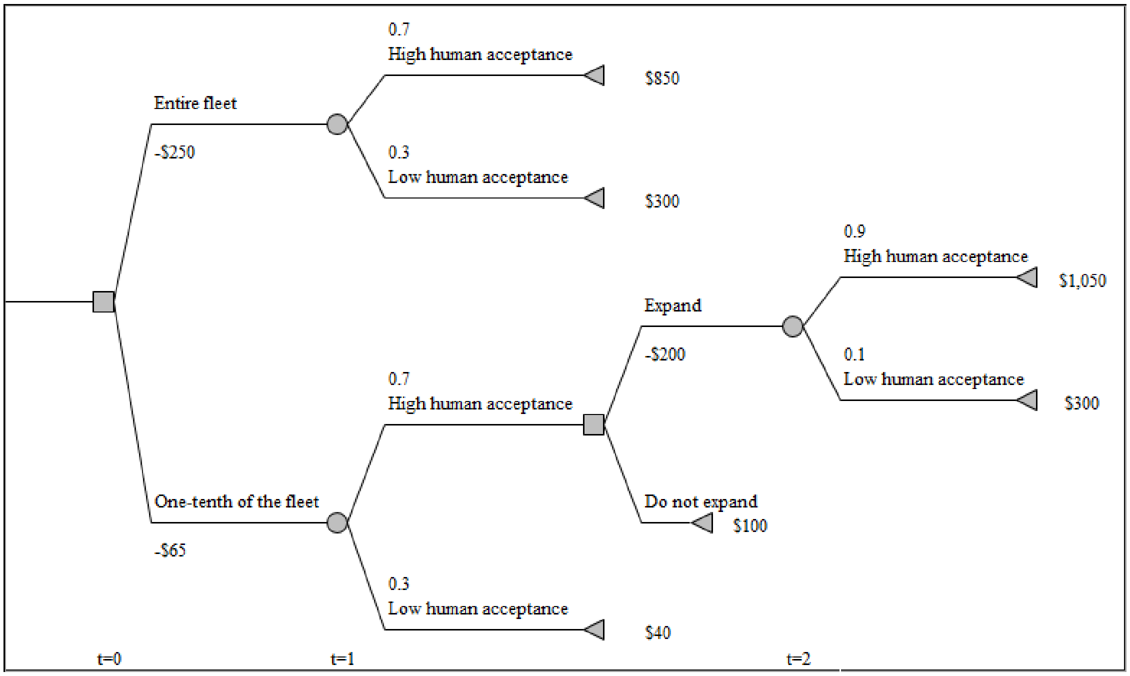

Figure 6. ALIAS Program Decision Tree with the Option to Expand.

Next year's decision is to decide whether to expand or not. The NPV of not expanding the ALIAS as of year one is $100 million. The NPV of expanding the program as of year one is:

$$NPV = -200 + \frac{(0.9)1,050 + (0.1)300}{1 + 0.05} = \$728.6 \text{ million}$$

Next year, the program manager would choose to expand, which has a monetary value of $728.6 million.

Now, by rolling back to today's decision, we can determine which alternative the program manager should choose today. The NPV of inserting the ALIAS to the entire fleet is the same, $402.4 million. The NPV of inserting the ALIAS to one-tenth of the fleet now becomes:

$$NPV = -65 + \frac{(0.7)728.6 + (0.3)40}{1 + 0.05} = \$432.1 \text{ million}$$

Therefore, the initial decision shifts to inserting the ALIAS to one-tenth of the fleet, with a program value of $432.1 million. The value of the option to expand is calculated as $432.1 – 402.4 = $29.7 million.

5. Results

The case demonstrates that the option to expand dramatically changed the initial decision. With the addition of the expansion option, the NPV of the project increased by $29.7 million, which is the value of the option to expand.

D. LIMITATIONS OF THE ANALYSIS

Although the analysis clearly illustrates the use of real options in defense R&D, it can be criticized by two important limitations. First, the analysis lacks empirical evidence. The study uses fictional yet practical data to analyze simplified cases. This analysis is sufficient to demonstrate the use and value of real options and the importance of real options thinking. However, one may argue that the analysis should be supported with empirical data from real cases, which is a reasonable critique. As discussed in the previous chapters, defense R&D is extremely critical for national security, thus undertaken under secrecy. Studying real R&D cases, therefore, requires confidential research, which can be done in a separate study. The second limitation is that the analysis uses subjective data, which is attributable to the characteristics of defense R&D—which is associated with project-specific risks—and of the DTA, which requires expected payoff and related probabilities as inputs. Due to this subjectivity, the quality of the analysis relies highly on the experience and knowledge of decision makers.

E. EVALUATION AND CONCLUSION

Despite its limitations, the analysis successfully combines the DTA approach with the case study method and produces simplified real option models. These practical and easy-to-apply models provide clear pictures that illustrate the use and the value of real options as well as the power of real options thinking in defense R&D projects. Although only three types of real options—options to defer, abandon, and expand—are analyzed in this thesis, the results of the analyses are attributable to the value of flexibility the real options provide. The cases and models are typical examples of defense R&D decision making and project valuation. Therefore, options to defer, abandon, and expand are not the only real options related to the defense R&D projects, nor are the models the only way to integrate real options into defense R&D projects. Since every R&D project is unique, its associated real options are also unique. Moreover, real options related to defense R&D projects can be used in several discrete ways. In this sense, the simple models presented in the thesis should be regarded as examples to gain strategic insights that help decision makers enhance their understanding on the use of real options.

This analysis, in turn, has three overarching results, which answer the research questions. First, real options to defer, abandon, and expand significantly improve the NPV of defense R&D projects. When the real options are strategically integrated into R&D projects, they provide decision makers with flexibility, therefore improving the value of the projects. Second, real options thinking has strategic value in shaping managerial decision making. The use of real options emphasizes the importance of real options thinking when deciding on defense R&D projects. Once options to defer, abandon, and expand are integrated into the projects, initial decisions of the program managers have dramatically changed. In this sense, the analysis shows that when managers employ real options thinking by accounting for flexibility, they are likely to make sounder decisions. Third, the DTA can practically be used to value the real options in R&D projects. The analysis views each R&D project as two different projects—one with the option and the other without it—and compares the NPV of these projects. The comparison provides the value of the flexibility attained, or the value of the specific real option. This aspect substantiates the assertion that the DTA is a practical tool for valuing real options in R&D projects.

V. SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

This chapter provides a comprehensive summary of the thesis, conclusions drawn from the analysis, and recommendations for further research.

A. SUMMARY OF THE THESIS

The purpose of the thesis was to illustrate the benefits of using real options in defense research and development (R&D) projects. To satisfy this purpose, I addressed not only the primary research question "how can real options be used in defense R&D?" but also secondary and more detailed questions. The ultimate aim of these questions was to find out whether 1) the DTA is preferred to the ROV approach in valuing defense R&D projects that include real options, 2) the "real options thinking" improves the net worth of the project and has significant effect on decision making, and 3) the value of real options can be calculated using the DTA approach. To this end, I organized the thesis into five chapters.

In Chapter I, I introduced the problems with evaluating defense R&D projects and sketched the outline of the thesis. First, I defined the defense R&D in accordance with the *Frascati Manual* (OECD, 2015), and presented a comparable defense R&D data, which was gathered from the OECD.Stat (2016a, 2016b) database. The data illustrated that countries, the United States being in first place, spend significant amounts on defense R&D budgets, which should be planned and allocated accordingly.

Next, I discussed the importance of defense R&D and the challenges associated with it. In this regard, defense R&D has several benefits for the respective country in preserving national security, deterring potential adversaries, leveraging the competitive position, and providing economic benefits. However, the nature of defense R&D projects—i.e., their uniqueness, long project lives, uncertain outcomes, and risks and uncertainties regarding the R&D process—pose important challenges for planning and capital budgeting. As analyzed in this part, the risks influencing the success of the defense R&D projects are mainly project specific, or private, risks, since no market that affects an R&D project exists.

Finally, in Chapter I, I presented the problems with current defense R&D project evaluation methods, which fail to account for necessary flexibility to deal with the risks and uncertainties associated with defense R&D projects. I suggested that real options is a practical tool to address existing problems. Although scholars acknowledge the value of the real options and the real options thinking, they differ on the appropriate approach—i.e., the real options valuation (ROV) or the decision tree analysis (DTA)—to model and value real options in defense R&D projects.

In Chapter II, I provided a comprehensive review of related literature. First, I examined the foundations of real options analogy, starting with the financial option pricing models—that is the Black-Scholes Model (1973) and the Binomial Model (Cox et al., 1979). I also analyzed the taxonomy of real options and defined options to defer, abandon, and expand, which are typical to defense R&D projects. Moreover, I revisited the similarity between financial options and real options, and analyzed the comparable inputs to work both financial option models and the ROV.

Second, I analyzed the debate between the ROV and the DTA supporters with the aim to determine the best approach for modeling and valuing real options in defense R&D projects. I reviewed extensive literature on ROV applications in R&D projects and presented the critiques of these applications. These critiques are mainly focused on the complexity of the process and the problems with underlying assumptions of the models; namely, constant volatility, lognormal distribution, and replicating portfolio. Most important of all is the replicating portfolio/no arbitrage assumption, which relies on market data, therefore assuming that the R&D project is exposed to market risks. However, as the DTA supporters argue, and as I discussed in the first chapter, defense R&D projects are mainly influenced by project-specific risks. Therefore, real options in defense R&D are better modeled and valued with the DTA approach.

Besides this debate, scholars are in agreement regarding the benefits of "real options thinking" in investment decisions, particularly in R&D projects. Real options thinking refers to the managerial flexibility that is integrated into the investment decisions to benefit from opportunities and protect against threats (Steffens & Douglas, 2007). However, although real options thinking has been widely accepted and real options research has been plentiful, real options applications in defense have been very scarce. In this regard, I asserted that this thesis would close the gap in the literature.

In Chapter III, I analyzed the methodology employed in the thesis. To present how the real options are used in defense R&D projects, I used the DTA approach along with the case study method and built simple models. The case study is a particularly important method that provides a detailed comprehension of specific concepts to help formulate larger studies. To this end, I selected three DARPA projects as cases and simplified them to enhance the reader's understanding of the use of real options.

I analyzed DARPA cases with the DTA approach, which provides managers with an important managerial tool to map out in a comprehensible manner all important decisions, chance events, associated probabilities, and expected benefits. In this chapter, I provided detailed steps to build and evaluate a decision tree. Moreover, I reviewed and responded to the two main criticisms of the DTA approach. The first one centers on the potential complexity of decision trees when built to reflect actual complex R&D projects. This criticism holds true to a certain extent; however, considering the readily available software, it is no longer a problem. The second criticism targets the discount rate that it is constant and reflects the riskiness of the project. This critique is flawed because 1) since defense R&D is exposed to private risks and funded by government funds, the constant risk-free interest rate is a highly relevant choice, and 2) the DTA adjusts for risk by properly defining alternatives and probabilities, not by increasing the discount rate.

In Chapter IV, I analyzed three ongoing DARPA R&D projects to model options to defer, abandon, and expand. In analyzing the cases, I initially built a decision tree for each project and calculated the NPV of the projects. Next, I incorporated the relevant real option and calculated the NPV of the projects once more. The analysis showed that real options added value to the projects. Furthermore, the difference between the two revealed the value of the respective real option. The first case was the CommEx program, illustrating the option to defer. When the program manager chose to defer the installation of the CommEx until the uncertainty is resolved, the NPV of the project dramatically increased. The second case evaluated the ACTUV project by integrating an option to abandon at the end of the testing phase. Since the program manager possessed an option to abandon the project provided the test results are poor, rather than bearing additional costs, the initial decision shifted, and the NPV of the project increased. The third case analyzed the ALIAS program with an option to expand. When the option to expand the installation of the ALIAS was incorporated into the decision tree the initial decision changed, and the NPV of the project increased.

Although the analysis lacked empirical data and relied on subjective data, the analysis successfully combined the DTA approach with the case study method and produced real options models that illustrate the use of real options in defense R&D projects. These simple models are valuable in that they provide strategic insights for defense decision makers and illustrate the importance of real options thinking. I only analyzed the three types of real options in this thesis; however, the results and conclusions are attributable to the value of real options in general.

B. CONCLUSIONS

Nations fund significant defense R&D budgets to preserve national security, deter potential adversaries, leverage their competitive positions, and provide potential economic benefits. Considering the characteristics and challenges of defense R&D, decision makers should abandon traditional methods and use real options in planning and evaluating defense R&D projects. The thesis, therefore, analyzed the use of real options in defense R&D. Accordingly, we can draw the following conclusions:

- Due to the private, or project-specific, risks associated with defense R&D projects, the DTA is a better approach than the ROV in modeling and valuing real options in defense R&D projects.
- Although the analysis only included the options to defer, abandon, and expand, the results and conclusions are applicable to the real options in defense R&D projects in general.
- When real options are strategically integrated into R&D projects, they provide decision makers with flexibility, therefore improving the value of the projects.
- Real options thinking has strategic value in shaping, and dramatically changing, managerial decision making, therefore leading to sounder decisions.

- The DTA can practically be used to value the real options in defense R&D projects. The difference between the NPV of each project with and without the applicable option provides the real option value, or the value of the flexibility.

C. RECOMMENDATIONS FOR FUTURE RESEARCH

Although substantial number of real options studies exist in the literature, research on defense R&D real options is extremely limited. Considering the significance of defense R&D for the respective country, studies in this domain should be extended. To this end, further research into the following areas is recommended:

- Applying the models to other R&D cases to further enhance the comprehension of real options thinking
- Producing new models for other types of real options
- Exploring confidential studies that examine real R&D cases with empirical data
- Undertaking real options studies regarding other areas of defense, such as acquisition

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APPENDIX A. DEFENSE R&D DATA FOR OECD COUNTRIES

This appendix provides a detailed defense R&D data for OECD countries for the period between 2010 and 2015. Defense R&D budget data are in Table 3, and Defense R&D budget data as percentage of total government R&D budget are in Table 4.

Table 3. Defense R&D Budgets for OECD Countries, 2010–2015.
Source: OECD.Stat (2016a).

Country	2010	2011	2012	2013	2014	2015
Australia	301.4	316.3	298.5	287.6	280.2	292.3
Austria	0.1	0.1	0.1	0.3	1.1	0.3
Belgium	4.9	4.8	4.7	4.6	4.6	..
Canada	273.8	227.6	257.0	233.5	..	..
Chile	..	0.2	0.1	0.2	..	..
Czech Republic	36.4	31.5	29.4	27.5	26.3	25.7
Denmark	9.8	7.4	7.2	7.2	7.6	7.7
Estonia	0.7	0.7	0.8	1.2	3.1	..
Finland	61.8	56.5	55.3	38.9	42.8	37.1
France	2,808.7	1,322.4	1,232.8	1,069.8	1,108.3	1,136.0
Germany	1,449.4	1,165.2	1,135.1	1,133.5	1,152.5	947.0
Greece	2.8	8.0	7.1	5.2	1.4	1.2
Hungary	4.7	0.4	2.0	2.5	1.0	..
Italy	81.2	84.3	78.8	81.7	85.2	..
Japan	1,535.0	883.6	991.6	1,545.8	1,472.0	1,352.2
Korea	2,163.3	2,406.8	2,755.5	2,911.6	2,739.1	..
Netherlands	89.7	86.2	90.4	67.7	67.4	69.1
Norway	104.4	105.0	106.2	107.0	107.3	111.0
Poland	..	..	213.4	163.1	182.1	..
Portugal	6.1	8.3	5.9	5.8	7.3	8.1
Slovak Republic	8.4	12.1	12.6	7.7	7.5	6.9
Slovenia	2.3	1.8	2.2	1.8	0.5	1.0
Spain	164.6	169.2	149.4	114.0	101.0	..
Sweden	248.3	248.5	273.1	135.8	130.7	114.9
Switzerland	14.3	..	15.5	..	18.4	..
Turkey	907.6	888.1	726.0	1,515.3	609.2	911.8
United Kingdom	2,469.7	1,870.0	2,056.2	2,092.9	2,307.5	..
United States	85,346.0	80,361.8	75,678.7	66,099.6	64,985.7	64,419.6

(1) Data are US$ millions, 2010 constant prices and purchasing power parities (PPPs).

(2) Data include defense R&D financed by governments and exclude civilian R&D financed by defense ministries (OECD, 2016).

(3) Data for some countries are missing since they were unable to supply data (OECD, 2016).

(4) Countries, such as Iceland, Ireland, Israel, Luxembourg, Mexico, and New Zealand, are excluded from the table because they had no data or zero R&D budgets.

Table 4. Defense R&D Budgets as Percentage of Total Government R&D Budget for OECD Countries, 2010–2015. Source: OECD.Stat (2016b).

Country	2010	2011	2012	2013	2014	2015
Australia	6.44	6.76	6.58	6.20	6.17	6.62
Austria	0.01	0.00	0.00	0.01	0.04	0.01
Belgium	0.18	0.18	0.17	0.16	0.15	..
Canada	3.23	2.99	3.41	3.14	..	..
Chile	..	0.03	0.02	0.02	0.03	0.02
Czech Republic	2.25	1.70	1.59	1.47	1.41	1.41
Denmark	0.43	0.31	0.31	0.30	0.31	0.32
Estonia	0.35	0.29	0.32	0.46	1.33	..
Finland	2.72	2.55	2.58	1.90	2.14	1.86
France	14.70	6.80	7.12	6.29	6.63	7.18
Germany	5.01	3.95	3.85	3.72	3.85	3.16
Greece	0.29	0.88	0.68	0.42	0.12	0.11
Hungary	0.62	0.06	0.27	0.17	0.15	0.64
Italy	0.66	0.73	0.72	0.79	0.83	..
Japan	4.77	2.64	2.91	4.62	4.42	4.36
Korea	13.27	13.80	14.84	14.78	13.48	..
Netherlands	1.57	1.47	1.67	1.23	1.22	1.22
Norway	4.32	4.34	4.36	4.19	3.98	3.86
Poland	..	..	7.15	5.22	4.77	..
Portugal	0.22	0.30	0.24	0.24	0.29	0.30
Slovak Republic	1.68	1.93	2.24	1.41	1.37	1.28
Slovenia	0.68	0.53	0.74	0.67	0.21	0.40
Spain	1.42	1.67	1.73	1.45	1.26	..
Sweden	7.56	7.80	8.05	4.00	3.75	3.34
Switzerland	0.47	..	0.43	..	0.48	..
Turkey	22.53	20.48	17.51	30.12	13.63	20.99
United Kingdom	18.24	14.48	16.19	15.32	16.85	..
United States	57.29	56.81	54.73	52.71	51.25	50.92
OECD - Total	**28.60**	**26.88**	**25.98**	**23.91**	**23.29**	**..**

(1) Data are percentages.

(2) Data include defense R&D financed by governments and exclude civilian R&D financed by defense ministries divided by total government R&D budget (OECD, 2016).

(3) Data for some countries are missing since they were unable to supply data (OECD, 2016).

(4) Countries, such as Iceland, Ireland, Israel, Luxembourg, Mexico, and New Zealand, are excluded from the table because they had no data or zero R&D budgets.

APPENDIX B. THE BLACK-SCHOLES OPTION PRICING MODEL

The Black-Scholes (1973) formula to calculate the values of a European call option is as follows. The formula and the notations are adapted from Trigeorgis (1996, pp. 89–91).

$$C = SN(d_1) - Xe^{-rT}\,\mathrm{N}(d_2) \tag{3}$$

where
$$d_1 = \frac{\ln(S/X) + (\mathrm{r} + \frac{1}{2}\sigma^2)T}{\sigma\sqrt{T}}$$

and
$$d_2 = d_1 - \sigma\sqrt{T}$$

for

C: European call option value

S: The value of the underlying asset

X: Exercise (strike) price

e: Base of natural logarithms = 2.718…

r: Risk-free interest rate

T: Time to expiration of the option

σ: The volatility measure, or the standard deviation of the returns

N(.): Cumulative standard normal density function

A number of assumptions—which Black and Scholes (1973) define as "ideal conditions" (p. 640)—should be present to work the model. Briefly, the model assumes no dividends and transaction costs for the underlying asset, returns from the underlying asset follow lognormal distribution, and the underlying asset volatility and the interest rate are both known and constant.

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APPENDIX C. THE BINOMIAL MODEL

The Binomial Model, which was first formulated by Cox et al. (1979), allowed a simplified valuation for options. The model shares similar assumptions as the Black-Scholes Model with one exception: it supposes that the stock prices follow a "multiplicative binomial process" rather than a lognormal distribution (Cox et al., 1979). However, as these process intervals become smaller, and as the multiplication process increases, stock prices approach a lognormal distribution: with an infinite number of bifurcation, the Binomial Model converges with the Black-Scholes Model (Trigeorgis, 1996). This characteristic implies that "the Black-Scholes formula can be derived from the Binomial Model" (Jao & Jaafari, 2003, p. 63). Figure 7 illustrates the multiplicative binomial process in one period.

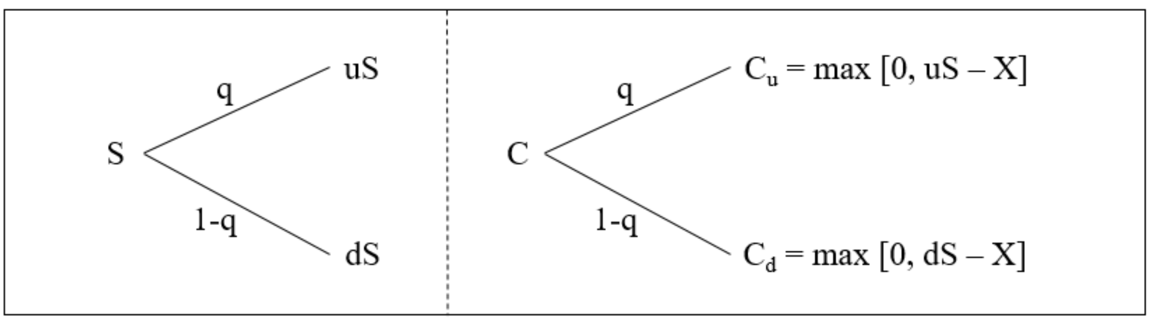

Figure 7. The Binomial Movement of the Underlying Asset Value (*S*) and the Corresponding Call Option Value (*C*) in One Period.
Adapted from: Cox et al. (1979).

The Binomial Model assumes that the underlying asset price (*S*) in a discrete period of time can only change to one of two levels: either up to *uS* (*u* is a multiplicative up factor) with a probability *q* or down to *dS* (d is a multiplicative down factor) with a probability *1 – q* (Cox et al., 1979). Similarly, the current value of the call option (*C*) can only become either *Cu* if the stock price increases to *uS*, or *Cd* if the stock price decreases to *dS*, with the same probabilities of *q* and *1 – q*, respectively (Cox et al., 1979). Note that if the underlying asset price is less than the exercise price (*X*), the call option is worthless (Trigeorgis, 1996). Accordingly, the call option value at the final nodes is calculated as the maximum of either zero or the exercise price less the asset value at the end of the period.

As I have noted earlier, since the option pricing models disregard the investor's risk attitude, the probability *q* is replaced by risk-neutral probability *p*, which "is the value *q* would have in equilibrium if investors were risk-neutral" (Cox et al., 1979, p. 235). Using this risk-neutral probability, the call option value (*C*) in Figure 7 can be found by solving the binomial tree by discounting at the risk-free interest rate (*r*) for one period (Cox et al., 1979):

$$C = [pC_u + (1-p)C_d]/1+r \ , \tag{4}$$

where

$$p = \frac{(1+r)-\mathrm{d}}{u-d}$$

Considering the replicating portfolio concept, to avoid the riskless arbitrage profit opportunity, the Binomial Model requires $u > (1+r) > d$, where $d = 1/u$ (Cox et al., 1979). Since the down factor *d* is the reciprocal of the up factor *u*, as the multiplicative periods increase, up and corresponding down movements recombine and the process turns into a lattice (Mun, 2002). For instance, Figure 8 illustrates the lattices for the underlying asset and the call option value in two periods.

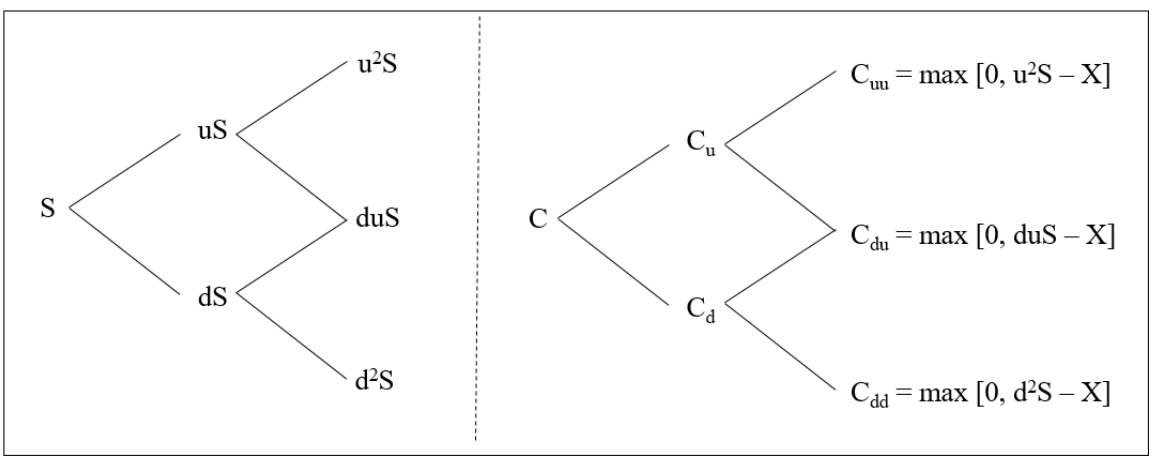

Figure 8. The Binomial Movement of the Underlying Asset Value (*S*) and the Corresponding Call Option Value (*C*) in Two Periods.
Adapted from: Cox et al. (1979).

In Figure 8, u^2S denotes the underlying asset value at the end of two periods provided its price increases in two consecutive periods; duS and d^2S have similar denotations. Likewise, C_{uu} denotes the call option value at the end of two periods if the underlying asset goes up in two consecutive periods; again, C_{du} and C_{dd} have similar denotations.

Consequently, to build the Binomial Model, we divide *T* (Time to expiration of the option) into any number of time-steps (*n*) to obtain the length of the discrete period of time (*h*). Next, we calculate the *u*, *d*, and *p* (risk-neutral probability) using the following formulas, which are adapted from Cox et al. (1979) and Mun (2002):

$$u = e^{\sigma\sqrt{h}} \ ,$$

$$d = 1/u \ ,$$

$$p = \frac{e^{r(h)} - d}{u - d} \ , \tag{5}$$

for

u: Multiplicative up factor

d: Multiplicative down factor

e: Base of natural logarithms = 2.718…

σ: The volatility measure, or the standard deviation of the returns

h: Length of the discrete period of time, or time-steps

p: Risk-neutral probability

r: Risk-free interest rate

In regard to the formulas, *u* and *d* represent the rate of returns, which are logarithmic—or continuously compounded (Trigeorgis, 1996). Once *u* and *d* factors are determined, the first binomial lattice is constructed to calculate the evaluation of the underlying asset value for each node. Then the second binomial lattice is built to calculate the call option values starting from the terminal node, in which the option value is *max [0, S – E]*. Using the terminal node values, the intermediate nodes and finally the initial node, which is the call option value, are calculated. This process is called "backward induction" and obtained through the following formula (Mun, 2002, pp. 156–157):

$$[(p)up + (1-p)down]e^{-r(h)} \tag{6}$$

Here, *up* denotes the value of the next upper node and *down* denotes the value of the next lower node. Since every node, except the terminal nodes, has corresponding up and down values in the following period, we can work the backward induction until we find the option value today. In this sense, the Binomial Model can be likened to solving decision trees (Brealey et al., 2008).

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2. Dudley Knox Library
   Naval Postgraduate School
   Monterey, California